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A Review of Strategic Mobility Models and Analysis

John Schank, Michael Mattock,
Gerald Sumner, Irwin Greenberg,
Jeff Rothenberg, James P. Stucker

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PREFACE

Strategic mobility encompasses the movement of forces (units, support, and resupply) from their home station to a destination where the force is to be initially employed. Questions involving strategic mobility range from planning for future force structures that are both affordable and operationally effective to using the available transportation assets in a manner consistent with commanders' operational objectives. Strategic mobility issues will become even more important if the United States reduces its forward deployed forces or if Third World contingencies require the presence of U.S. forces.[1]

This report documents part of a RAND project entitled "Achieving Maximum Effectiveness from Available Joint/Combined Logistics Resources." The research was sponsored by the Logistics Directorate of the Joint Staff (JS–J-4) and was conducted under the Acquisition and Support Policy Program of RAND's National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense and the Joint Staff. The first two tasks of the project surveyed the needs and opportunities for responsive logistics/operations command and communication, and conceived and evaluated enhancements for conventional ammunition.[2]

This document summarizes the findings of the third task and presents a strategy that should improve the future analysis of strategic mobility issues. The research and recommendations are aimed at supporting and improving the strategic mobility analyses performed by the Logistics Directorate of the Joint Staff, (JS–J-4) specifically by the Studies, Concepts, and Analysis Division (SCAD), which conducts long-range planning and force structure analyses. Also as part of Task 3, RAND hosted a conference on strategic mobility modeling, which was attended by over 70 representatives from the Joint Staff, the Office of the Secretary of Defense, the military services, private industry, academia, and other research institutions.

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[1]As this document is entering the publication process (fall 1990), the United States is in the midst of its largest deployment of units and equipment since World War II. Operation Desert Shield is being closely monitored by numerous organizations to understand the implications on future force structures, the required quantities and types of transportation assets, and the procedures and parameters contained in mobility models.

[2]See S. C. Moore, J. Stucker, and J. Schank, *Wartime Roles and Capabilities for the Unified Logistic Staffs*, RAND, R-3716-JCS, February 1989; and *Enhancing Joint Capabilities in Theater Ammunition Management*, RAND, R-3789-JS, 1991.

This report should be of particular interest to personnel within the Department of Defense who use strategic mobility models and to modeling experts in industry and academia who are involved in the research and development of hardware, software, and algorithmic technologies.

SUMMARY

The complexity of strategic mobility issues suggests that analysts must be supported by large computerized models, which are generally used to estimate some aspect of transporting combat and support forces and their sustainment from the United States to a combat theater. Currently, however, organizations often have difficulty understanding the models and using them to support their analysis objectives.

This study was designed to assist the Logistics Directorate of the Joint Staff (JS/J-4) to understand and improve the capabilities of the major computerized models and databases used for analyzing strategic mobility questions, to survey the various uses of strategic mobility models, evaluate the attributes and limitations of the major existing models, and determine whether another computer model would serve the directorate's needs better than does its current model.

Each organization engaged in activities involving strategic mobility analysis may have several different types of analysis objectives, and several different organizations may address the same type of objective. The various objectives of strategic mobility analysis are grouped into three broad planning categories:

- *Resource planning,* which is typically long-range force planning and programming.
- *Deliberate planning,* which is mid-range deployment planning that encompasses the development and analysis of operational plans.
- *Execution planning,* including both the short-range crisis action planning before an engagement begins and the continuing planning and replanning as execution proceeds.

This study concentrated on resource planning, which is the type of planning performed by the Logistics Directorate's Studies, Concepts, and Analysis Division (SCAD). Models dedicated to deliberate and execution planning were explored as well.

LIMITATIONS OF CURRENT MODELS

Our analysis indicates that the strategic mobility models we examined—MIDAS, RAPIDSIM, TFE, FLOGEN, and SEACOP—share the following basic shortcomings:

- They all work in one direction only.
- Their credibility outside the organizations that use them is limited.
- They do not sufficiently recognize uncertainty.
- Their objective functions are too narrow and rigid.
- Their output measures do not adequately serve analysts' needs.

Furthermore, the pre- and post-processing functions that surround all the models also have several problems.

All the major current models are basically deterministic simulations or have major simulation components; i.e., they assign cargoes to transportation assets according to specific rules and then simulate movement of the cargoes through the transportation system. The question they are designed to answer is one of "capabilities assessment": Given a set of transportation assets, what is the closure profile for a set of forces, support units, and resupply? In this sense, they all work in one direction, from cargoes and transportation assets to delivery dates for forces.

Requirements studies, however, need to turn the question around and ask: *What is the best mix of transportation assets* for achieving the desired closure profile for a given set of forces, support units, and resupply? With existing models, analysts cannot directly answer this second question; they must utilize special post-processing programs to obtain an approximate solution, which is then tested with additional model runs.

No one model of the current suite of mobility models is generally accepted throughout the defense community. Having been developed a decade ago or more, the models use dated hardware, software, and algorithmic technologies; and they have been patched or modified to the point where it is difficult to understand how they work or to verify if they are operating correctly. Their complexity often results in mobility analysts needing the model builders to actually run the models. These problems have led most analysts to view the models as "black boxes." Even though analysts do not completely understand the model they use, they understand far less about other mobility models and, therefore, they generally prefer the one they are familiar with to others.

Current models fail to recognize or incorporate the numerous uncertainties that characterize war. The answers that result may "work" for only a very narrow set of assumptions. If enemy actions or changes in commanders' objectives deviate from that narrow set of assumptions, the force structures and plans may no longer be adequate.

The heuristic rules used to prioritize cargoes and then assign them to transportation vehicles determine the de facto objective functions of

the models. Those objective functions are too narrow and rigid. For example, current models do not adequately consider the interrelationships between different cargoes, they sometimes result in using more transportation assets than necessary, and they often do not reflect the CINCs' true preferences for the sequence of cargo arrivals.

A final problem with current models is that their output measures do not adequately provide decisionmakers with the operational effect of alternative mobility plans or delivery options. Instead, they simply provide the delivery dates of cargoes and the utilization of transportation vehicles and port facilities. Ideally, decisionmakers should know the combat value of alternative delivery options in order to select among different force closure profiles. This may involve in future model development the linkup of warfighting models to mobility model outputs to provide the correlations between unit closures and their implications to combat effectiveness.

In an investigation of the processing activities that must occur before and after the model is run, it was found that the pre-processing functions of developing, checking, and aggregating the necessary input data, and the post-processing functions of checking, correcting, disaggregating, and displaying model results typically consume the majority of the overall analysis effort. Although model runs may take only a few hours, the overall analysis process takes many months. Furthermore, these pre- and post-processing functions hinder and constrain mobility analysts, who must rely on outside organizations for assistance in developing and checking the data. The end result is that the analyst feels isolated from the analysis, further contributing to doubts about the credibility of analysis results and recommendations.

NEW MODELS UNDER DEVELOPMENT AND THEIR LIMITATIONS

Because of the shortcomings of existing mobility models, several organizations are developing new models. The Ace Reinforcement Model (ARM) is under development at Supreme Headquarters, Allied Powers Europe (SHAPE) Technical Center for the combined commands, and the Global Deployment Analysis System (GDAS) is being developed at the Army's Concepts Analysis Agency (CAA). Four new mobility models are being developed for the U.S. Transportation Command (USTRANSCOM) and its components. The Airlift Deployment Analysis System (ADANS) is being developed to replace FLOGEN as the Military Airlift Command's (MAC's) primary tool for planning, scheduling, and analysis. The Strategic Sealift Planning System

(SEASTRAT) and the Scheduling Algorithm for Improving Lift (SAIL) are being developed for the Military Sealift Command. The Military Traffic Management Command is developing a model called the Strategic Deployment System (STRADS) to replace its current scheduler. Finally, the Flow and Analysis System (FAST), which is an integrated version of the preceding three, is being developed for USTRANSCOM.

Although these new models contain innovative features that will overcome certain limitations of the older models, they still do not account adequately for the uncertainties of wartime, use sufficiently flexible and broad objective functions, or produce output measures that are operationally oriented. More important, none of them focus on transportation requirements determination, which is a primary resource planning task the J-4 must perform. The new models, like the current ones, are geared to capabilities assessment. In addition to these generic limitations, each of the Transportation Component Commands model has specific shortcomings that prevent it from being appropriate for resource planning. STRADS, for instance, does not consider intertheater movements, which are the major focus of JS/J-4 analyses, and ADANS and SEASTRAT each consider only one mode of transportation (airlift and sealift, respectively).

RECOMMENDED STRATEGY

For the near term, JS/J-4 should continue to use MIDAS and RAPIDSIM because the staff is familiar with those models and the models are at least as good as others currently available. However, specific steps should be taken to improve the pre- and post-processing functions in order to enhance analyses. For example, routines ought to be developed to generate movement requirements, to check input data for errors and for consistency, and to aggregate cargo records. In addition, a commercial relational database management package should be procured to assist in organizing and manipulating the data, and a commercial graphics package should be obtained to summarize and display model outputs.

In the long term, however, JS/J-4 should develop a new mobility model specifically for resource planning analysis that takes advantage of new and emerging technology. The new model should better represent the CINCs' preferences for the delivery of cargoes, increase the "robustness" of mobility plans,[1] and be valid and credible.

[1]Deriving CINCs' preferences and evaluating the robustness of a set of transportation assets may require a combat-oriented model. Therefore, two models may be needed to adequately address the "preferred" mix of transportation assets—one to provide transpor-

To ensure that the new model has credibilty throughout the mobility analysis community, a group of experts should oversee the development of the model, set sound guidelines during the development effort for enhancing the model's transparency, provide thorough documentation, and ensure that validation continue throughout the development cycle.

Two parallel, but coordinated, prototype efforts are recommended: one using mathematical programming techniques and one using knowledge-based modeling techniques. Both prototypes would provide better understanding of the relative advantages and disadvantages of each. The final model may actually be a combination of the two techniques.

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tation assets for a given scenario, and one to evaluate the combat effectiveness of different forces that can be delivered with the resulting transportation mix. An existing combat simulation model most likely can be used to interface with the new transportation requirements model.

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GLOSSARY

ADANS	Airlift Deployment Analysis System (MAC model)
AI	Artificial intelligence
ALD	Available to load date
APOD	Airport of debarkation
APOE	Airport of embarkation
CAA	Concepts Analysis Agency (Army)
CFE	Conventional Forces in Europe
CINC	Commander-in-Chief
CJCS	Chairman, Joint Chiefs of Staff
CMNA	Chairman's Military Net Assessment
CNASP	Chairman's Net Assessment for Strategic Planning
COA	Course of action
CONPLANS	Contingency plans
CONUS	Continental United States
CPA	Chairman's Program Assessment
CRAF	Civil Reserve Air Fleet
CSCMS	Combat Support Capability Measurement System
CULT	Common-user land transport
DAP	Deployment Analysis Prototype (model)
DoD	Department of Defense
DPG	Defense Planning Guidance
DPQ	Defense Program Questionnaire
EAD	Earliest arrival date
ES	Expert system
FLOGEN	Flow Generator (MAC model)
GRC	General Research Corporation
JCS	Joint Chiefs of Staff
JDA	Joint Deployment Agency
JDS	Joint Deployment System
JDSSC	Joint Data Systems Support Center
JMNA	Joint Military Net Assessment
JMPAB	Joint Materiel Priorities and Allocation Board
JOGS	Joint Operational Graphics System
JOPES	Joint Operation Planning and Execution System
JOPS	Joint Operation Planning System
JPAM	Joint Program Assessment Memorandum
JS	Joint Staff
JS/J-3	Operations Directorate of the Joint Staff

JS/J-4	Logistic Directorate of the Joint Staff
JS/J-5	Strategic Plans and Policy of the Joint Staff
JS/J-8	Force Structure, Resource and Assessment of the Joint Staff
JSCP	Joint Strategic Capability Plan
JSPS	Joint Strategic Planning System
JSR	Joint Strategic Review
JTB	Joint Transportation Board (at the Joint Staff)
KBS	Knowledge-based simulation
LAD	Latest arrival date
LIC	Low intensity conflict
LOE	Level of effort
LPD	Logistics Planning Division (of the JS/J-4)
MAC	Military Airlift Command
MAPS-II	Mobility Analysis and Planning System (MTMC model)
MARP	Mission area review panel
MIDAS	Model for Intertheater Deployment by Air and Sea (OSD and JS model)
MODES	Mode Optimization and Delivery Estimate System (JDS model)
MSC	Military Sealift Command
MTMC	Military Traffic Management Command
NARDAC	Navy Regional Data Automation Center
NATO	North Atlantic Treaty Organization
NCA	National Command Authority
NDRI	National Defense Research Institute
NMSD	National Military Strategy Document
NSSS	NATO Sealift Sizing Study
O&M	Operations and maintenance
OCONUS	Other-than-CONUS
OJCS	Organization of the Joint Chiefs of Staff
OPLAN	Operation plan
OPORD	Operation order
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
OSD(PA&E)	Office of the Secretary of Defense (Program, Analysis, and Evaluation)
PACAF	Pacific Air Forces
PC	Personal computer (microcomputer)
POD	Port of debarkation
POE	Port of embarkation
POM	Program Objective Memorandum

POMCUS	Prepositioned overseas material, configured to unit sets
PPBS	Planning, Programming, and Budgeting System
PREPO	Prepositioned equipment
PWRM	Prepositioned war reserve materiel
RAPIDSIM	Rapid Intertheater Deployment Simulator (model)
RDD	Required delivery date
RIMS	Revised Intertheater Mobility Study
RLD	Ready to load date
SACLANT	Supreme Allied Command, Atlantic
SAIL	Scheduling Algorithm for Improving Lift (MSC model)
SCAD	Studies, Concepts, and Analysis Division (JS/J-4)
SEACOPS	Strategic Sealift Contingency Planning System (MSC model)
SEASTRAT	Strategic Sealift Planning System (MSC model)
SHAPE	Supreme Headquarters, Allied Powers Europe (NATO)
SITAP	Simulator for Transportation Analysis and Planning (JDSSC model)
SMD	Strategic Mobility Division (of the JS/J-4)
SPOD	Seaport of debarkation
SPOE	Seaport of embarkation
STRADS	Strategic Deployment System (MTMC model)
SUMMITS	Scenario Unrestricted Mobility Model for Intratheater Simulation (OSD model)
TAWG	Transportation Analysis Working Group
TCC	Transportation Component Command
TFE	Transportation Feasibility Estimator (JOPS model)
TOC	Transportation operating command
TPFDD	Time-phased force deployment data
USA	United States Army
USAF	United States Air Force
USCENTCOM	United States Central Command
USEUCOM	United States European Command
USFORSCOM	United States Forces Command
USMC	United States Marine Corps
USN	United States Navy
USPACOM	United States Pacific Command
USTRANSCOM	United States Transportation Command

I. INTRODUCTION

The U.S. military doctrine adheres to a strategy of forward defense and flexible response. One basic premise of the U.S. global strategy is to defend the nation by fighting our foes on foreign soil. To accomplish this objective, the United States relies on its strategic mobility system to deploy and sustain military forces worldwide. To provide airlift and sealift assets to move large numbers of personnel, equipment, and support materiel from the continental United States (CONUS) to foreign locations, the U.S. military either procures and operates such assets or enters into agreements with commercial organizations to provide them.

Questions concerning the composition and use of the strategic mobility system are complex and diverse. Decisions must be made, for example, on the number and type of transportation assets required to meet our global commitments. These decisions must be made in light of budget constraints, potential tradeoffs between the types and numbers of combat and support forces, and the readiness and positioning of those forces. Another strategic mobility issue concerns the effective use of available transportation assets to deliver combat and support forces in a manner consistent with commanders' operational objectives.

Strategic mobility issues will become even more important and complex in the future because of the various changes underway that affect national strategy.[1] For example, political changes within the Warsaw Pact and the resulting reduction in tensions in Europe are giving rise to initiatives to reduce our deployed forces. Such European force reductions will require a reexamination of the numbers and types of equipment and supplies that are prepositioned and of the transportation assets needed to reinsert forces in Western Europe to protect our allies and fulfill treaty obligations when mobilization and deployment warning times are greatly increased. More important, the lessening military tension with the Soviet Union is counterbalanced by the increasing unrest and friction in the Third World. As a result, the military is placing more emphasis on the potential need to send forces where it has little established presence. Mobility analysts therefore must address a series of vital questions regarding where forces may

[1]The importance of strategic mobility is recognized at the highest levels of the U.S. military: Secretary of Defense Cheney has named strategic mobility as one of his top priority issues.

have to be sent, what forces will be required, and whether the required location has an infrastructure to support airlift and sealift operations. Finally, constant or shrinking defense budgets will lead to reduced force structures and difficult choices on the development and procurement of new systems. In this changing era, the strategic mobility system, along with all combat and support systems, must rely on careful and thorough analysis to identify preferred plans and policies.

Because strategic mobility issues are so complex and diverse, analysts require large computerized models to help them identify options and understand the implications of various alternatives. The models are used to examine or predict some aspect of the transport of combat and support forces and their sustainment from CONUS to theater during mobilization/deployment. Based on what has to be moved and what transportation assets are available, these models typically determine preferred transportation routes and the cargo that should be assigned to those routes, and they simulate the movement through the system to estimate when forces are delivered into the theater. Many mobility models exist, and several new ones are being developed to overcome the problems or limitations of current models.

RESEARCH MOTIVATION

Many different organizations, using a variety of models, perform mobility analyses, including the Assistant Secretary of Defense for Program Analysis and Evaluation (ASD/PA&E), various service groups, the staffs of the theater commanders, and the transportation "providers."[2] The Joint Staff plays a major role in addressing strategic mobility issues, particularly the Logistics Directorate (JS/J-4). The JS/J-4 examines transportation capabilities and resource requirements questions, helps develop and check operational plans (OPLANs) to ensure they are transportationally feasible, and performs critical mobility functions during low-intensity conflicts (LICs), such as Grenada and Panama. Within the JS/J-4, the Studies, Concepts, and Analysis Division (SCAD) performs two major types of mobility analyses: In requirements analysis studies, it estimates the numbers and types of airlift and sealift assets needed to meet various commitments; and in capability determination studies, it estimates the capability afforded by a given set of transportation assets.

[2]The United States Transportation Command (USTRANSCOM) was created to coordinate the joint issues of strategic mobility. Its component commands, which perform the actual transportation functions, include the Military Airlift Command (MAC), the Military Sealift Command (MSC), and the Military Traffic Management Command (MTMC).

SCAD recently experienced problems with mobility models while conducting their Revised Intertheater Mobility Study (RIMS), which examined the preferred mix of airlift, sealift, and prepositioning needed to meet U.S. global commitments. The study took more than two years to complete, requiring over 400 model runs and substantial pre- and post-processing activities, including the development of over 40 different routines comprising 10,000 new lines of computer program code. Even with that commitment of time and effort, however, the study examined only a few of the options and left some questions unanswered. In addition, SCAD analysts experienced difficulty in using their strategic mobility model, MIDAS (Model for Intertheater Deployment by Air and Sea).[3]

Realizing similar studies would be required in the future, SCAD asked RAND to examine the military mobility models currently in use and those under development, and to recommend a strategy for improving JS/J-4's capability for conducting strategic mobility analysis. Questions of interest included whether MIDAS or another available model could be improved, whether one of the models currently being developed should be adopted, whether a totally new model should be developed, and how emerging technology could improve the analysis process.

RESEARCH OBJECTIVES AND APPROACH

The objective of our study was to assist the JS/J-4 in understanding and improving the capabilities of the major computerized models and databases used for analyzing strategic mobility questions. We examined the use of strategic mobility models during the peacetime planning process and the ability of existing models to address changes in mobility plans caused by the uncertain and dynamic aspects of wartime. We addressed this objective through three subtasks:

1. Enumerate the various objectives of strategic mobility analysis and the analytic capabilities that have been developed to meet those objectives. Interview relevant organizations to understand the issues they address, the models they use, and the problems they see.

[3]Part of the difficulty resulted from the model's lack of transparency, or perceived "black box" nature. Without an understanding of what went on inside the model, SCAD analysts could look only at the results and compare them with what they believed would happen during real operations. When results were questioned, the issue arose of how the model worked and how to modify it.

2. Understand the current capabilities of existing models. Compare and contrast the major existing models in terms of model assumptions and data inputs, analytic capabilities, algorithms, ease and cost of using the models, and limitations that constrain the ability to meet desired objectives.
3. Develop functional descriptions of new models and of improvements to current strategic mobility models and databases.

SUMMARY OBSERVATIONS AND RECOMMENDATIONS

All of the models we examined were developed 10 to 20 years ago and use outdated hardware, software, and algorithmic technologies.[4] Furthermore, they have been substantially modified, or "patched," over time. Few people understand these models, they are difficult to use, and they generally lack credibility throughout the mobility analysis community.

The existing models also address very narrow analysis questions and provide only limited assistance to analysts in understanding the effect of perturbations or unexpected events (the uncertainties of war). The models we examined were apparently designed to answer questions concerning the feasibility of transportation plans; and they work in ways that make it difficult for analysts to address resource requirements questions, as shown by the problems SCAD experienced during the RIMS.

Based on our observations of current mobility models and the analysis needs of the SCAD, we believe the JS/J-4 would greatly benefit from the development of a new model, one that is specifically designed to address resource requirements questions. This model should take advantage of new and emerging technologies to improve basic model characteristics, such as transparency, credibility, and validity.

The development strategy must consider ways to build a model that has a richer, more "realistic" objective function—that is, has the ability to address different utility measures or combinations of preferences. Finally, a new model should provide measures that help analysts understand the potential effect of wartime uncertainties and the marginal costs and benefits of additional or fewer assets.

We believe at least two modeling approaches have merit—mathematical programming and knowledge-based modeling. Because

[4]We examined the MIDAS, RAPIDSIM, TFE, FLOGEN, and SEACOP models in detail.

there are numerous unknowns, we recommend that both approaches be investigated through parallel, but coordinated, prototyping efforts. The knowledge gained through these prototype models then can be used to structure the new model.

ORGANIZATION

The next section examines the users and uses of strategic mobility models. Section III compares several of the major models currently used within the community, describing in general terms how they work, how they are similar, and how they differ. Section IV describes the limitations we see with current models and how those limitations affect mobility analysis. Section V outlines our short-term and long-term recommendations for the JS/J-4. Finally, there are three appendixes: App. A, which is a supplement to Sec. III, provides a more detailed description of current models; App. B describes knowledge-based modeling; and App. C describes mathematical programming techniques.

II. USERS AND USES OF STRATEGIC MOBILITY MODELS

The intent of this section is to establish a context in which to consider modeling technology as a means of improving the state of strategic planning and to consider prospects for transferring such technology from one kind of planning to another.

We begin by defining three types of strategic mobility planning, and then use those definitions as a way of dividing our discussion of the various users of mobility models. Finally, there is a discussion of factors that tend to discourage communication of ideas within the using community.

TYPES OF STRATEGIC MOBILITY PLANNING

Various agencies use strategic mobility models for planning purposes, but primarily the models find application in resource planning, deliberate planning, and crisis action planning.

Resource Planning

Resource planning encompasses the program development and related policy research that is conducted in the Planning, Programming, and Budgeting System (PPBS). Although mobility studies in resource planning may presume specific theater scenarios, the analyses are collectively meant to inform coordinated long-range resource planning for total forces. These studies are generally of two types: capability assessments, which determine the force closure that can be supported by a given set of lift assets, and requirements studies, which estimate the lift assets necessary to support a given force closure.

In capability assessments, a strategic mobility model is used to assess how soon a particular set of transportation assets can effect theater closure of a particular set of forces, support, and resupply, given the constraints of scenario and cargo priorities. Examples of such analyses at the Joint Staff include the Defense Planning Questionnaire (DPQ), which supports NATO planning, and the Joint Military Net Assessment, which is submitted annually to Congress. Although capability assessments theoretically are one-shot uses of the model, more runs are almost always needed to assess the implications

of uncertainty. To explore degrees of risk with a given force structure and operational objectives, the model may be exercised numerous times with different versions of scenario assumptions.

Requirements studies ask the question, "How many of what types of transportation assets are necessary to move cargo to the specified destinations, satisfying a particular desired closure schedule?" The result of the analysis describes a set of transportation assets, or perhaps the required increments to a baseline set of assets. As will be discussed in Sec. IV, conducting this type of study with the currently available mobility models is necessarily an iterative process. At the Joint Staff, the important recent example of a requirements study is the RIMS, which required over 400 MIDAS runs between October 1986 and April 1989.[1]

Deliberate Planning

Deliberate planning denotes theater-oriented operations planning, ordinarily OPLAN development. In this case, the mobility analyses focus on the use of lift assets in specific but notional conflicts. The initial purpose of the analyses is to determine whether lift assets are capable of supporting the theater CINC's closure requirement; if results are negative, mobility analyses then help provide the bases for negotiating militarily sensible closure requirements that *can* be supported. The ultimate product of these analyses is a specific transportation schedule.

Crisis Action Planning

Crisis action planning refers to planning that takes place immediately before and during real conflicts. Mobility models are used to allocate actual available lift (1) to help determine feasible courses of action (COAs) and (2) to specify transportation schedules for COAs that are ultimately undertaken. The process is dynamic, the schedule being reworked daily as the COA unfolds. This contrasts with deliberate planning, where a successful transportation schedule signals the end of the planning process.

It is tempting to view these three types of planning as long-range, medium-range, and short-range planning. Doing so, however, promotes the notion that they are somehow interconnected phases of a single comprehensive planning process. As currently constituted, they are in fact separate planning processes with different objectives; they are

[1]All models mentioned in this section are described in detail in Sec. III and in App. A.

conducted by different people, they use different models, and the environments in which they take place differ considerably.

These differences are important for understanding why there seems to be no vigorous tradition of idea sharing within the strategic mobility modeling community, even though the major models have certain similarities (as will be described in Sec. III) and at a high level have the common purpose of planning and directing effective transport of combat resources from CONUS to theater.

JOINT STAFF USE OF STRATEGIC MOBILITY MODELS: RESOURCE PLANNING

Use of strategic mobility models by the Joint Staff occurs mainly in the Studies, Concepts & Analysis Division of the J-4 Logistics Directorate.[2] The following paragraphs focus on SCAD's uses of MIDAS, its most widely used model.

Use of MIDAS at SCAD

SCAD does most of its analyses in support of other divisions within J-4 and other directorates of the Joint Staff. The main uses of MIDAS are resource planning exercises in support of various aspects of DoD's PPBS process, which ultimately results in the biennial President's Budget and the Six-Year Defense Program (SYDP).

MIDAS simulations are particularly important in contributing to the Joint Strategic Planning System (JSPS), a biennial cycle of reports through which the CJCS formally transmits recommendations on national military strategy, directs operations planning, and generally supports the PPBS. The JSPS was revised in 1990. The major components of the new JSPS are: (1) the Joint Strategic Review (JSR), (2) the National Military Strategy Document (NMSD), (3) the Joint Strategic Capabilities Plan, and (4) the Chairman's Program Assessment (CPA).[3]

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[2]The Joint Data Systems Support Center (JDSSC), a support organization to the Joint Staff, develops and maintains mobility models, most notably RAPIDSIM. JDSSC also provides services, including performing actual model runs, to organizations that use their models.

[3]The JSR is a review and assessment activity that culminates in the Chairman's Guidance report, which in turn provides direction for preparing the NMSD. The NMSD (formerly the Joint Strategic Planning Document) conveys the national military strategy and its implications for force structure. The JSCP tasks the theater CINCs to develop OPLANs. The CPA (formerly the Joint Program Assessment Memorandum) conveys the CJCS's assessment of the balance and capabilities of the Program Objective Memorandum force. Direction for the new JSPS comes from CJCS MOP 7, issued January 30, 1990.

Contributing to the JSPS reports are a variety of studies and documents to which SCAD, in turn, provides analytic support. For example, SCAD's capability assessments become part of the Chairman's Net Assessment for Strategic Planning (CNASP) and the Joint Military Net Assessment (JMNA). The CNASP is an integral part of the NMSD; the JMNA is an annual report to Congress, but also provides inputs for both the JSR and the CPA. SCAD also provides estimates of lift requirements for the Risk Evaluation Force that is developed as part of the JSR. Although in recent years these particular efforts have accounted for only 10 to 15 percent of MIDAS runs, the activity is expected to increase substantially with the current intent at DoD to incorporate multiple scenarios into the PPBS process.

In addition to MIDAS's primary use for resource planning, SCAD uses it in support of combined planning, while other divisions in J-4 use the model for deliberate planning. Combined (e.g., NATO) planning is supported by MIDAS in periodic analyses such as the Defense Planning Questionnaire (DPQ), which details planned U.S. support to NATO, and nonrecurring studies, such as the NATO Sealift Sizing Study, which determined transportation assets necessary to support force commitments for the European theater. The theater CINCs' deliberate planning is supported indirectly by MIDAS analyses that are used in the development by J-4/LPD (Logistics Planning Division) of the logistics and mobility annexes to the Joint Strategic Capabilities Plan. MIDAS is also used for numerous ad hoc studies that address special requests by other agencies from within and outside of the Joint Staff.

During the 42-month period beginning October 1986, 1447 MIDAS simulations were produced, accounting for 24 separate studies, exclusive of updates. About two-thirds of the simulations were for requirements studies; one-third was for capability assessments. Figure 1 represents the distribution of the simulations among major kinds of study objectives. Simulations for particular studies numbered as few as two and as many as 471; in Fig. 2, the studies are ordered along the X axis by size (numbers of simulations) to illustrate this study-to-study variation.

Other Strategic Mobility Models at the Joint Staff

Several other mobility models are used at the Joint Staff, both within SCAD and within JDSSC. For example, in 1990 SCAD is using a PC adaptation of MIDAS called MINOTAUR, which is less detailed and provides faster turnaround than does MIDAS. The use of MINO-

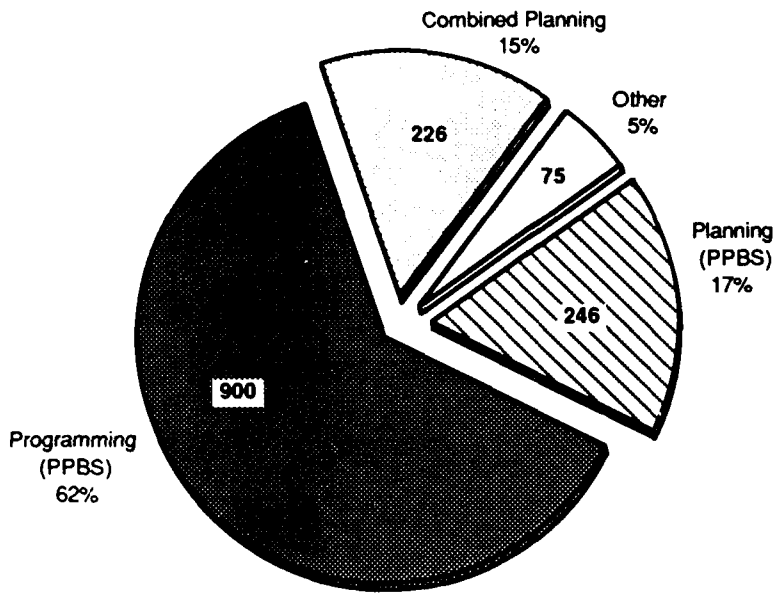

Fig. 1—Distribution of MIDAS runs by type of study, October 1986 through March 1990

TAUR is in part a reaction to global changes in military threat that are propagating different kinds of planning scenarios, with increasing emphasis on smaller and more numerous conflicts. The other center that supports mobility analysis in the Joint Staff, JDSSC, primarily uses an intertheater mobility model called RAPIDSIM to provide transport inputs to war games and military exercises. JDSSC uses RAPIDSIM also to support various special-purpose capability studies, such as analyses of requirements for NATO and U.S. civil reserve airlift forces. In addition to RAPIDSIM, JDSSC occasionally uses MIDAS, MINOTAUR, and intratheater mobility models.

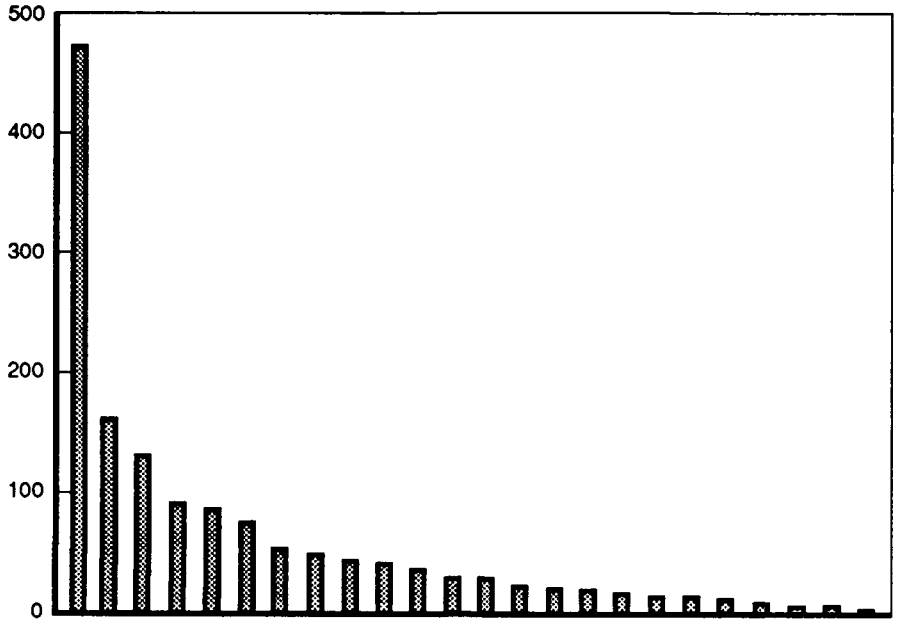

Fig. 2—Distribution of MIDAS studies by size, October 1986 through March 1989

OTHER USERS AND USES OF STRATEGIC MOBILITY MODELS

Other primary users of strategic mobility models within DoD include the Office of Secretary of Defense (OSD), the four service departments, the theater CINCs and their service components, USTRANSCOM, and the Transportation Component Commands (TCCs), which include Military Sealift Command (MSC), Military Airlift Command (MAC), and the Army's Military Traffic Management Command (MTMC). In addition, there are users representing the combined commands, such as NATO or SACLANT, who coordinate with the U.S. users to plan for coordinated transportation actions that are required of all member nations to meet treaty commitments. In our visits with representatives of these agencies, we observed that all utilize some sort of strategic

mobility model or related computer support, though pencil and paper are frequently employed where computer models would be useful.

Figure 3 summarizes these users and their uses. The rows are categories of users, the columns are the three types of planning activities, and the cells indicate examples of the analyses performed.

Whereas the Joint Staff uses mobility models primarily for resource planning, other organizations use them for all three types of planning: resource planning, deliberate planning, and crisis action planning. In the discussion of users and uses that follows, we focus as much on the planning processes as the mobility analyses in order to emphasize the contexts of model use.

Resource Planning

Strategic mobility analysis is a part of the PPBS effort, not only at the Joint Staff but also at the service headquarters and at OSD. The programming phase of PPBS begins when the service headquarters prepare their five-year time-phased POM submissions in response to the Defense Planning Guidance (DPG). These submissions are statements of resource needs that address the planning guidance and subject to the resource constraints presented in the DPG. At the same time,

	Resource Planning	Deliberate Planning	Crisis Action Planning
OSD (PA&E)	NSSS POM review		
Joint Staff	RIMS, CPA JMNA	DPQ, OPLAN review	JTB, close-held plans
Svc HQ	POMs		
CINCs		OPLANs, GTFTs	COA analysis, validation
Service components		GTFTs	Cargo requirements
TRANSCOM and the TCCs	Equipment	Movement tables	Movement schedules
Combined commands		Combined lift	

Fig. 3—Users and uses of strategic mobility models

the services must prepare databases for input into the Joint Staff JSPS efforts. The service headquarters, or their supporting agencies, use mobility models to assess whether the forces projected in the POM are transportationally feasible.

Service headquarters also engage in numerous mobility studies that are only indirectly related to PPBS but that are still very important for resource planning. For example, there are studies to identify strategic deployment bottlenecks and to conduct cost-effectiveness tradeoffs of alternative deployment options (POMCUS vertical fill, containerization, fast sealift, management of transport assets, etc.). The services have their own models for these purposes, including TRANSMO at the Army, MARS at the Navy, and MASS at the Air Force. The results of these studies ultimately affect deployment policy, hence the planning premises contained in such models as MIDAS.

During the programming phase of PPBS, OSD receives the POM submissions from the service headquarters and scrutinizes them for consistency with the IPS, CPA data, and current assets. OSD also tries to identify better mixes of combat forces and better ways to manage those forces. They use mobility models to address such problems as assessing the changing role of airlift vs. prepositioning in Europe, estimating capabilities of alternative transport systems such as the C-17, or determining the least-cost combination of mobility programs that meets objectives and is operationally feasible.

After the President's Budget goes to Congress, OSD may be called upon by congressional members to address specific transport-related questions, and this requires additional use of the models.

Deliberate Planning

As noted earlier, deliberate planning is peacetime operations planning, oriented particularly to OPLAN development. The process is typically keyed to a two-year cycle and is initiated by tasking from the Joint Staff to CINCs of the combatant commands. The primary tasking document is the JSCP, which defines the specific planning objective and apportions the major combat forces and transportation assets to be used. The JSCP might be viewed as the culmination of the PPBS process; it is the Joint Staff's statement of how the resources resulting from past PPBS processes are to be allocated during the ensuing two years. Mobility analyses at the Joint Staff help develop these allocations.

Upon tasking, the CINC develops the concept of operations, which is passed along to the theater service components along with the list of apportioned combat forces and transportation resources. The

components specify the necessary supporting forces and supplies, translating the whole into a time-phased list of cargo requirements, or time-phased force deployment data (TPFDD).

At this point, the TPFDD must be analyzed to determine if it is transportationally feasible, given the apportioned transportation assets. If it is not "feasible," the cargo list is reworked until it is. If it is feasible, the time-phased list is certified as Grossly Transportationally Feasible. Gross feasibility analysis may be performed by the service components on their individual cargo lists or by the CINC on the consolidated component lists. At least one computerized mobility model is available for this purpose, the Transportation Feasibility Estimator (TFE), which is used at USPACOM; but it was not in use at the other theaters we visited. The Joint Staff J-4 Logistics Planning Division (LPD) also uses TFE for the intermediate review it conducts on the grossly feasible TPFDD.

Next, refinement conferences are held to determine sourcing (replacing hypothetical TPFDD units with actual ones) and more detailed transportation feasibility. The conferences have representation from the CINC, the service components, and other commands that support the OPLAN, such as USFORSCOM, USTRANSCOM, and the TCCs.

Before the transportation conference, the TCCs use mobility models to prepare initial movement tables for the CINC's TPFDD, adding in cargo requirements necessary for lift support. The Military Traffic Management Command uses a model called Mobility Analysis and Planning System (MAPS-II) to develop schedules for CONUS movement. The Military Airlift Command uses FLOGEN for airlift scheduling, and the Military Sealift Command uses SEACOP for sealift scheduling.

The initial schedules generated by the TCCs typically cannot satisfy the CINC's desired closure profile, and much conference time is consumed in negotiating transport shortfalls; this essentially is a process of adjusting the CINC's cargo priorities so that they reconcile with lift capabilities. The final product of the conferences is supposed to be a Transportationally Feasible TPFDD, but typically many runs of the TCCs' models are required after the conference.

The Combined Commands do not take part in OPLAN development, but they do receive U.S. strategic forces information distilled from OPLANs; for example, the Defense Planning Questionnaire supports NATO operations planning. The Combined Commands take a multinational view of operations planning and presumably focus more strongly on host nation support and the interfaces between intertheater and intratheater movement. They conduct their own strategic mobility analyses but nevertheless rely heavily on mobility inputs provided by the Joint Staff.

The deliberate planning process summarized above applies to planning for large, theaterwide conflicts since the preponderance of effort in peacetime contingency planning is of this sort. Planning for low intensity conflicts (LICs) appears to be more ad hoc, possibly because LICs are believed to present fewer problems of allocation of scarce combat and logistic resources. At USCENTCOM, for example, CONPLANS are developed for LIC situations; CONPLANS are much less detailed than OPLANs, lacking TPFDDs, sourcing, and movement schedules. At USEUCOM, the OPLAN TPFDD is parceled into force modules, and some of the modules are earmarked for particular kinds of LICs.

A variety of models is used for these different aspects of deliberate planning, but there is also frequent reliance on manual methods, mostly for tasks relating to gross feasibility. We were told that simple computer models were much needed. The models that are available were seen as too difficult, too data-intensive, or otherwise not directly applicable.

Crisis Action Planning

In contrast to deliberate planning, which is periodic and addresses hypothetical conflicts, crisis action planning responds to specific time-sensitive contingencies. It begins with assessments by a CINC and then by National Command Authorities (NCA) and the Chairman, Joint Chiefs of Staff (CJCS), that a developing situation may warrant a military response. In a series of phases, the crisis is assessed, a course of action is developed and selected, execution is planned, and an OPORD initiates execution.

In crisis action planning, transport analysis is typically a joint effort of the theater CINCs, the theater service components, USTRANSCOM, and the TCCs. The CINCs initially develop COA options, employing estimates of cargo requirements from the service components and deployment estimates from USTRANSCOM or the TCCs. Transportation options and availabilities are, of course, a consideration in this process.

After the NCA selects one of the COAs, the CINC initiates the execution planning phase. The objective is essentially to replicate the product of deliberate planning, but the product must reflect the crisis situation, current strategic constraints, and current availability of combat forces and logistic support. Several options for developing execution plans are available: (1) an existing OPLAN may be pulled from the shelf and modified to the current situation, (2) an existing CONPLAN may be selected and supplemented with a time-phased forces

list and transport schedule, or (3) the plan may be built from scratch. The service components again specify cargo requirements. The CINC "validates" these requirements, including a determination of whether they can be transported by available lift within the desired closure window; and the TCCs prepare the corresponding movement schedules. The CINC then publishes an OPORD, but the decision to execute the OPORD belongs to the NCA.

During the execution phase, the cargo requirements and sourcing contained in the OPORD are updated daily, or as needed, to reflect the progress of the conflict. Service components specify incremental changes in cargo requirements, and these are validated by the CINC. Preparation of incremental, or daily, movement schedules during execution is diverse. MSC prepares schedules for sealift, the Numbered Air Forces (who "own" the transport aircraft) schedule airlift, and the MTMC Area Commands schedule CONUS movement. Throughout all of this, the Joint Transportation Board (JTB) at Joint Staff resolves conflicts among competing demands for lift from different theaters, and theater-level JTBs resolve conflicts over lift among service components within theaters.

Thus, in crisis action planning, transportation analysis is employed in three phases: COA development, execution planning, and execution. Allocation of these responsibilities seems to depend on the nature of the crisis—for example, the size of the conflict, whether the CINC has adequate staff support, whether planning is to be closely held at high military levels, or whether the United States will employ forces from a mix of combatant commands. For some crises that are closely held, most of the planning may be conducted at the Joint Staff, and the J-4 Strategic Mobility Division (SMD) may take the lead in transportation planning.

In crisis action planning, there currently is very little use of computer tools for transportation analysis except for the TCCs, which rely heavily on the same models used in deliberate planning. There are initiatives for new models in process (described in Sec. III), and the Joint Operations Planning and Execution System (JOPES) is still on the horizon, but we heard of no quick feasibility estimators in current use that were not strictly experimental.

Differences in Planning Environments

To understand the prospects for transferring modeling technology, it is instructive to consider differences in the planning environments. These translate into different kinds of planning constraints, perspectives on the use of planning technology, and ultimately measures of

success for "jobs well done." Figure 4 describes the three planning types in terms of some of the more important dimensions of the planning environment.

Resource planning is long-range planning constrained by educated, but notional, guesses about scenarios; it relies on projections for input data. The data are received in batches from other agencies, but the planning cycle allows for pre- and post-processing. Personnel build skills over time through actual experience, and computers are used extensively. The measure of a good resource planning study seems to be *how consistently the projected data inputs reflect the notional scenario constraints.*

In contrast, *deliberate planning* is fairly short-range planning, also with notional scenario constraints, relying for inputs on data estimates. The data are generated in batches by diverse sources from within the planning infrastructure, as opposed to resource planning where most data come from outside. But again, there is time for some pre- and post-processing. Some personnel build skills over time through actual experience, but most are rotated to other assignments. Computer support is strong in some agencies, but weak in others. A successful study in this case seems to be measured by *how well the estimated cargo requirements "flow" against estimated lift, subject to the notional scenario.*

	Resource Planning	Deliberate Planning	Crisis Action Planning
Planning horizon	6 years	30+ days	5-7 days
Scenario constraints	Notional	Notational	Actual
Transport inputs	Projected	Estimated	Actual
Cargo inputs	Projected	Sourced	Actual
Data access	Batch	Batch/on-line	Real-time
Planning cycle	2 years	2 years	1 day
Experience base	Actual	Actual	Simulated
Computer support	Strong	Uneven	Weak

Fig. 4—Planning environments for strategic mobility analysis

Crisis action planning is extremely short-range planning with actual scenario constraints, relying on actual data for inputs. The data are real-time, and there is virtually no time for pre- and post-processing. For LICs in certain theaters, personnel have built skills over time through actual experience; for larger conflicts, where there has been less opportunity for practice, personnel must build skills through experience that is only simulated. Use of computer support keyed specifically to crisis action transport planning is rare. Success in transport analysis is measured by *whether schedules are actually capable of execution in the real world in wartime.*

COMMUNICATION IN THE STRATEGIC MOBILITY ANALYSIS COMMUNITY

Because of shared similarities in the uses and applications of strategic mobility models, one might expect to find routine communication of ideas relating to strategic mobility analysis among users. One similarity, for example, is that all users of strategic mobility models address pieces of the same transportation problem, although from different planning perspectives. In addition, the models themselves share certain methodological similarities. Finally, all models have common problems in their application, such as difficulties with input data, and "felt needs" for simpler model alternatives. Despite these similarities, no organized, routine exchange of ideas relating to strategic mobility analysis exists, probably because of the differences catalogued above.

Communication of Ideas Varies

We found reasonably strong communication *within* the three planning "subcommunities" (resource, deliberate, and crisis action planning), but only weak communication *among* those subcommunities.

Communication within subcommunities benefits from the interactions among agencies that are a natural part of the planning processes (i.e., PPBS review processes, OPLAN refinement conferences, crisis action planning for LICs, and crisis exercises for large conflicts). There also are occasional multiagency working groups and review sessions that bring planners together, such as those supporting the development of JOPES. There are also interesting lapses; for example, the use of TFE in deliberate planning seems to depend more on the interest and background of the specific persons involved than on the planning need, and OSD users use MIDAS options that are possibly useful but unknown to JS users.

Communication among the subcommunities seems to be at best opportunistic, coming about primarily through informal networking and, to a lesser extent, the rotation of military personnel from one planning function to another. Although a single organization may be involved in more than one of the three types of planning, the personnel in those organizations generally are not; they typically specialize. Other sources that may play a role in fostering communication are modeling contractors and the interactions on strategic mobility modeling that occurs during the Military Operations Research Society meetings. In January 1990, the Joint Staff sponsored a three-day meeting of users, modelers, and contractors that was novel with respect to its diverse attendance.

Ideas That Need Exchanging

Several kinds of benefits could be derived from more structured communication and from eventual joint initiatives among the strategic mobility subcommunities. Some of these benefits would include sharing of modeling technology, resolving data problems, and exchanging substantive planning information.

Transfer of Modeling Technology. Computerized modeling seems to be underexploited in much of the strategic mobility analysis community. For example, crisis action planning obviously has the most difficult environment of the three planning arenas, and therefore one might expect to find considerable and creative user-friendly computer support of that activity. However, we found little evidence of such support. To the contrary, computer support is weak, and procedures are relatively ad hoc nearly everywhere except at the TCCs, and possibly at CENTCOM, which has had considerable recent experience with LICs. Computer support is stronger for deliberate planning, but that strength varies from theater to theater.

The need for simple, rough-cut models was expressed at several locations, and the value of exchanging information and experience appeared obvious.

Data Problems. Difficulties with data seem to be pervasive in the strategic mobility community, and some of these will require multiagency efforts to resolve. If the database used by planners in one agency is "owned" by another agency, then planning may be impeded by simple data access. For example, OSD and the Joint Staff rely on the services for data inputs during program review, and corrections to the data sets are the source of vexing delays. Another data problem is standardization. For example, results of analyses by different agencies in resource planning may be inconsistent because one is based on

programmed cargo requirements, another on current unsourced cargo requirements, and another on sourced requirements. There also is frequent failure to agree on the values of planning factors, such as port throughput factors or airplane or ship stowage factors. A final problem is serious data shortfalls. For example, there is no current system that would provide complete availability information for civilian and military sealift in the event of crisis action.

Exchange of Planning Information. One area of missed opportunity is the failure to capture, retain, and provide access to substantive information that originates in one planning arena and may be useful in another. For example, deliberate planning for large conflicts typically involves considerable effort in negotiating the tradeoffs between CINC priorities and lift capabilities; presumably there are lessons learned here that would be valuable for crisis action planning, if they could be captured and retained in a form that could be accessed quickly.

This could work in the other direction also; resource and deliberate planners might benefit from insights into CINC priority tradeoffs that are expressed in the heat of crisis action planning. Finally, since deliberate planning has heretofore put little emphasis on LICs, and since planning for LICs may become more important in the near future, deliberate planners might have something to learn from crisis action planning, where there has been real wartime experience with LICs.

III. DESCRIPTION OF CURRENT AND EVOLVING MOBILITY MODELS

In this section, we examine five of the major strategic mobility models currently being used in the defense community—MIDAS, RAPIDSIM, TFE, FLOGEN, and SEACOP—and briefly describe several mobility models that are under development. The intent of this section is to provide readers with a fuller understanding not only of the individual models, but also of the process that all of the current models follow. To that end, we begin with an overview of the steps by which a typical mobility model currently processes data and arrives at an output.

Having laid down a foundation for understanding the generic process that these simulation models follow, we next compare the five current models in terms of the tasks they perform, the way they model the transportation system, their solution characteristics, and their costs in time. The purpose of the comparison is to weigh the relative merits of the major current models in order to determine whether one of the existing models might serve the Joint Staff's needs better than its current model, MIDAS.

We conclude the section with a brief discussion of six strategic mobility models under development.

DATA FLOW OF A STRATEGIC MOBILITY MODEL

All the current models we examined process data in similar ways: Each model uses several inputs in the form of data files, all the models use similar algorithms to simulate the transportation system, and they all produce similar outputs (see Fig. 5).

Input Files

Typically, four files provide input for the simulation models: a requirements file, a PREPO file, a transportation resources file, and a scenario file. The model then assigns cargoes to transportation assets according to certain rules and simulates cargo movement through the transportation system.

The first input file is the *requirements* file, which provides data on the movement requirements, including records for all the forces, their

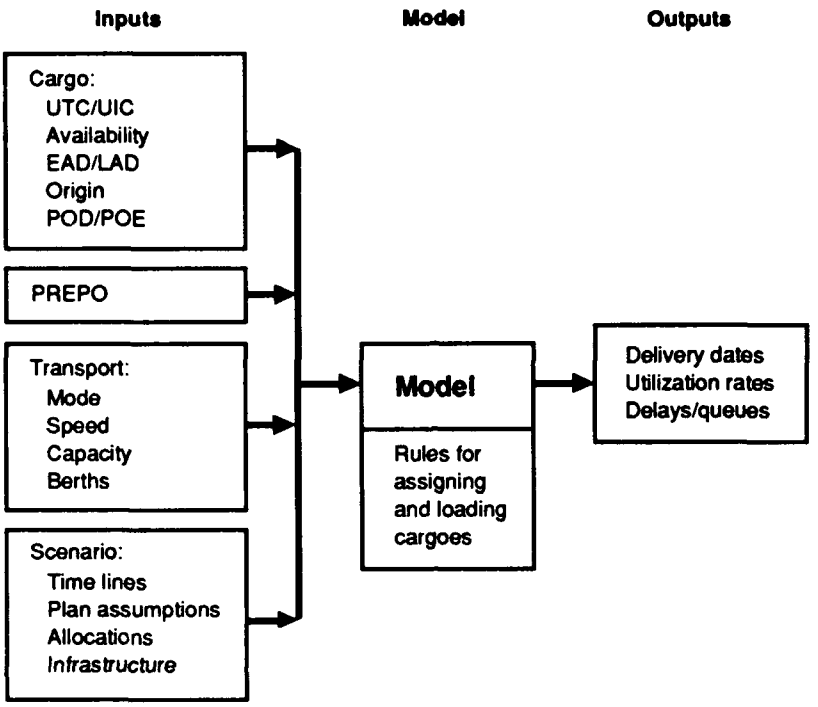

Fig. 5—The current mobility model analysis process

support, and necessary resupply. Each piece of cargo has identification numbers; weight, area, and volume characteristics; origin and destination identifiers; the time when it becomes available; the time when it must arrive at its destination; and many other data descriptors. For Joint Staff and OSD studies, these data typically are developed by service organizations.

The *PREPO* file describes those cargoes that have already been prepositioned near the overseas port of debarkation (POD). One example is POMCUS (Prepositioned Overseas Material, Configured to Unit Sets) and another is the Maritime Prepositioned Ships. Often this is not a separate file but a part of the requirements file. Using specified codes, an input record can indicate which of the movement requirements have been prepositioned. These records then do not compete for available intertheater lift.

The *transport resources* file describes the transportation resources. It provides speeds, capacities, loading and unloading capabilities, and other descriptors for different types of air, land, and sea transportation. This file, or a similar one, contains information on available routes and port (airport or seaport) locations, capacities, and constraints. All of this information usually comes from the transportation suppliers, the TCCs.

Finally, the *scenario* file contains data on timing (when mobilization begins, when war starts, etc.), on the availability of airlanes and sealanes (e.g., if the Suez Canal is open, if U.S. planes can overfly Egypt, etc.), and on the other major planning assumptions for a particular model run.

After simulating cargo movement through the transportation system, the model produces closure profiles for the forces and information on the utilization of assets. The output indicates the time each cargo arrived at its destination; which ships, planes, and facilities were used; how often they were used; and to what capacity. Most models also provide information on bottlenecks or delays in the system.

The Strategic Mobility Analysis Process

All of the current models use the same solution technique—deterministic simulation—and they follow basically the same steps to arrive at a delivery profile.[1] To fully understand these models, therefore, it is helpful to outline the various steps of a typical model. The framework we have used is to divide strategic mobility analysis into separate tasks, some of which take place within models, and others of which occur outside the models. The nine tasks are given below and shown in Fig. 6.

1. Merge files.
2. Aggregate records (by ports, routes, ships, or cargo).
3. Prioritize records.
4. Select modes (i.e., air or sea for those with no chosen mode).
5. Schedule cargoes.
6. Simulate movements.
7. Prepare textual output.
8. Prepare graphical output.
9. Check and correct.

[1]Deterministic simulation refers to the fact that the models are nonrandom and that they imitate a real world process, as opposed to a Monte Carlo simulation that uses random elements.

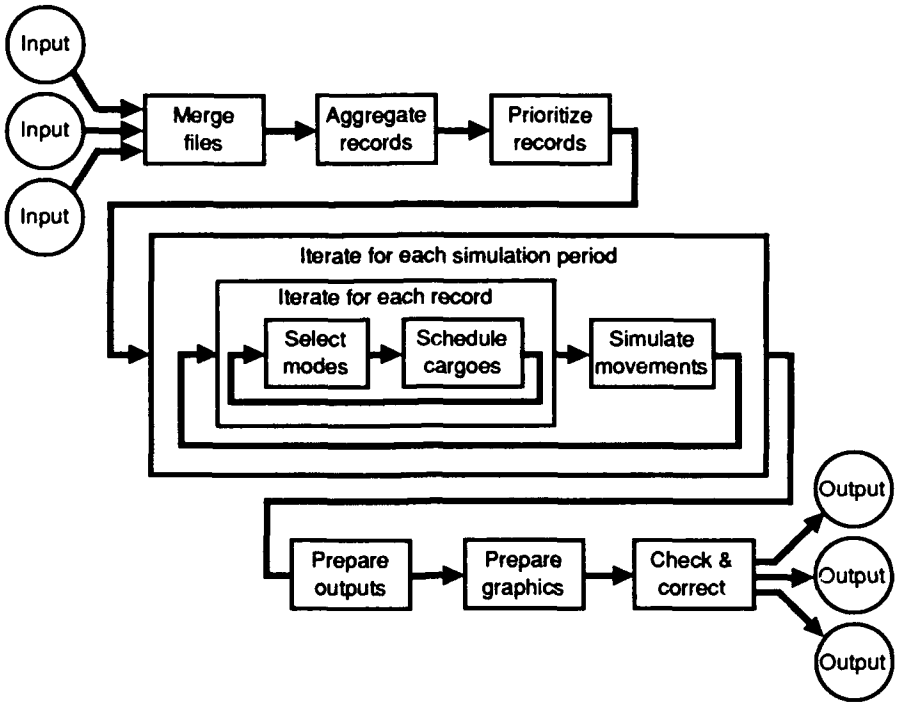

Fig. 6—Strategic mobility analysis may be divided into nine tasks

Task 1: Merge Files. Because the input data needed are generally not readily available or not available in the correct format, the first step is to prepare the various raw input files needed by the model. These files can come from many sources. For example, in outyear studies using the MIDAS model, input may come from the individual services, indicating what forces they are expecting to field in the particular outyear being studied. Because the outyear is a hypothetical case, this kind of information is not readily available on the JOPS or JDS. These files from the services are merged and aggregated and put into the format required by the model. The input format may be quite intricate; in the RAPIDSIM manual, for instance, some 124 pages are devoted to documenting the input format for ship characteristics, plane characteristics, target delivery dates, etc.

Task 2: Aggregate Records. Strategic mobility problems tend to be very large, sometimes involving 100,000 or more different cargoes

being shipped by thousands of vehicles to hundreds of destinations. Processing so many records can consume a tremendous amount of computer time, and therefore it saves time and money to aggregate records when aggregation will reduce computing time without adversely affecting the fidelity of the simulation. Aggregation is generally done in conjunction with the merging and massaging of the data (Task 1 above).

There are several different types of aggregation: cargo aggregation, port (node) aggregation, route (link) aggregation, and ship or plane (transportation asset) aggregation.

- *Cargo Aggregation*: Cargo requirement lists tend to be voluminous. For example, in its raw form, a large TPFDD can consist of more than 100,000 records. Usually it is computationally infeasible to examine so many records; therefore, the records are aggregated for similar pieces of cargo requiring transport from the same origin to the same destination at nearly the same time.
- *Port Aggregation*: Computation expense also motivates aggregating ports, as the complexity of the transportation problem increases exponentially with the number of ports. Several nearby ports (typically all ports within one day's sailing distance of each other) will be grouped into one "centroid," which shares in the characteristics of all the ports. However, this results in some loss of fidelity; for example, queuing behavior will be different for the aggregated port, and this may result in blindness to certain system bottlenecks. The loss in fidelity must be weighed against the cost associated with additional detail.
- *Route Aggregation*: Route aggregation is usually a direct consequence of port aggregation. If two sets of ports have each been aggregated into a separate centroid, then all the possible routes involving those two sets of ports will be aggregated as well. Route aggregation may also reflect convoying.
- *Transportation Asset Aggregation*: Transportation assets, such as planes, may be aggregated. For example, MIDAS models air transport as a flow (i.e., a pipeline), based on the number of planes, average cargo capacity, average speed, and average utilization rate. This is feasible for planes because MIDAS simulates day by day, and planes can fly from almost any origin to any destination in a day or less. Since ships generally take several days to reach their destination, this type of aggregation is not used for sealift.

Task 3: Prioritize (Cargo) Records. In addition to knowing "what" to ship, the model needs to know "when" to ship it. Thus, the next step is to rank cargo records in order of shipping priority. Priorities are usually based on a measure of desired delivery date expressed in the TPFDD. Cargo records are then sorted according to this order.

Task 4: Select Modes.[2] Airlift and sealift each has its advantages and disadvantages. "Small" loads can be transported quickly with airlift, and much larger loads can be transported by sealift, albeit at a much slower rate. Different types of planes and ships are better suited to some types of cargo than others. Thus, selection of the appropriate "mode" for each piece of cargo can be a nontrivial problem. The mode decision is usually based on rules that take into account the type of cargo, the travel time by air or by sea to the final destination, the date when the cargo will be available at the airport or sea port, and the required delivery date.

Task 5: Schedule Cargoes. Scheduling cargo is perhaps the most important function of a strategic mobility model. Cargo scheduling is based on the selected mode, the cargo's priority, and the availability of ships or planes to carry it. Typically this is done using heuristic rules (rules of thumb) that work on a day-by-day basis, with some look-ahead.

In sealift, all models look first for partially loaded ships and fill those before starting on empty ships; nevertheless, the probability is high that at the end of each scheduling day, some partially loaded vehicles remain.[3] Models typically move all partially loaded ships at the end of each "day."

Task 6: Simulate Movements. Once the model schedules cargo, it can then begin simulating movements. Ships and planes are loaded, sailed, and then unloaded. Usually only ships are discretely simulated; planes are represented by some kind of flow calculation, which gives a ton-miles capacity figure for each day. Some models provide the capability to track individual ships or planes as they make their appointed rounds.

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[2]In most strategic mobility models, these next few steps are repeated many times, as is indicated in Fig. 6. The "Select Modes" and "Schedule Cargoes" steps are repeated for each piece of cargo, within each simulation period. The "Simulate Movements" step is repeated for each simulation period.

[3]The issue of partial loading (ships sailing without full loads) often comes up in discussions of the relative efficiency or optimality of alternative shipping schemes. Partial loads were cited as a problem in RIMS, which indicated that "a limiting characteristic of the MIDAS sealift scheduling algorithm was 'light' loading of ships." This "problem" seems inevitable in any strategic mobility model because cargoes seldom match the size of any vessel, and therefore partial loads are common. The more types of vehicles and special cargo/vehicle matchups required, the more partial loads result.

Task 7: Prepare Output. After the simulation has been run for a specified period—e.g., 30, 90, or 120 "days"—tabular reports are prepared. The most common report shows the "closure profile," indicating what cargo arrived when, and indicating which shipments did not meet the target dates. Another typical report shows ship usage, such as how many sails each ship made in the first 90 days. A model may also produce a detailed database tracing the movements of each piece of cargo.

Task 8: Prepare Graphics. Because the tabular reports tend to be long, detailed, and difficult to comprehend, summary graphics may be prepared for analysis. They are usually based on the same data as the tabular reports. The most common graphic shows two curves: actual cumulative tons delivered (by day), and the requirement for cumulative tons delivered (by day). Some models can produce maps showing the locations of transportation assets at any particular time.

Task 9: Check and Correct. Once the tabular and graphical reports have been prepared they are checked; and if any problems are found, corrections are made either to the input database or the model itself. Then the model is run again. Generally this process is not automated; instead, an analyst must pore through reams and reams of output to find any mistakes or contradictions. Because of the sheer size of the output, mistakes may go unnoticed for days, weeks, or months.

Additional Elements in the Process

In addition to the primary transportation model, the strategic mobility analysis process may include many supporting models, and this dependence on other models can result in problems. From the very beginning, "raw" data input for the model may in fact have come from other models. For example, if the Joint Staff is doing an outyear study using MIDAS, they may need input from the Army concerning the force and support it hopes to field in the future. The Army would come up with a force and then run their FASTALS model to calculate the support needed for the force, and the output from this model would be forwarded to the Joint Staff as input to their analysis. Using "raw" data for the mobility model that may have already been "cooked" by another model can obviously affect the reliability of the output: The final output of the strategic mobility analysis process will share in the weaknesses of all the models used in support of the analysis.

The human experts and analysts who prepare the data and run the models are often the sole repositories of knowledge concerning how to merge files, aggregate records, and prioritize cargo to conduct a

particular analysis. None of the models completely automates this "pre-processing" task; instead the analysts manually manipulate some data for each run. Usually this task is not documented, which may lead to problems when other analysts try to replicate results using the same or a similar model. It may also lead to accusations, however unwarranted, that data may have been "cooked" so that model results would support a particular policy.

COMPARISON OF THE CURRENT MODELS

Having described the basic process by which deterministic simulation models arrive at delivery outputs, we can now compare the individual features of the selected current models. Although models can be compared using numerous properties, we have distilled four important features for our comparison: (1) the strategic mobility analysis tasks covered, (2) the way the transportation system is defined and modeled, (3) the solution characteristics, and (4) the cost in time.

Strategic Mobility Analysis Tasks Covered

Each of the current models covers different groupings of the nine tasks described above (see Fig. 7),[4] and each relies on other models or human intervention to cover the other steps in the analysis. Since different models cover different steps, they are not freely interchangeable. For example, TFE covers only three of the nine steps: Schedule Cargoes, Simulate Movements, and Prepare Outputs. The other steps are carried on outside of the model either manually or by supplemental programs. As Fig. 7 shows, MIDAS and RAPIDSIM have the widest coverage, performing five of the nine tasks. MIDAS is the only model that automates the "Prioritize Records" task. Note that none of the models automates the first two tasks, "Merging Files" and "Aggregating Records," which are both left to pre-processing routines (either computerized or manual).

The Way the Transportation System Is Defined and Modeled

When comparing mobility models, it is important to view the entire span of the strategic mobility system. Figure 8 shows that the span ranges from the home location of a movement requirement to the final area of employment.

[4]"Mode Selection" is omitted for FLOGEN and SEACOP, since these models consider only one mode in isolation.

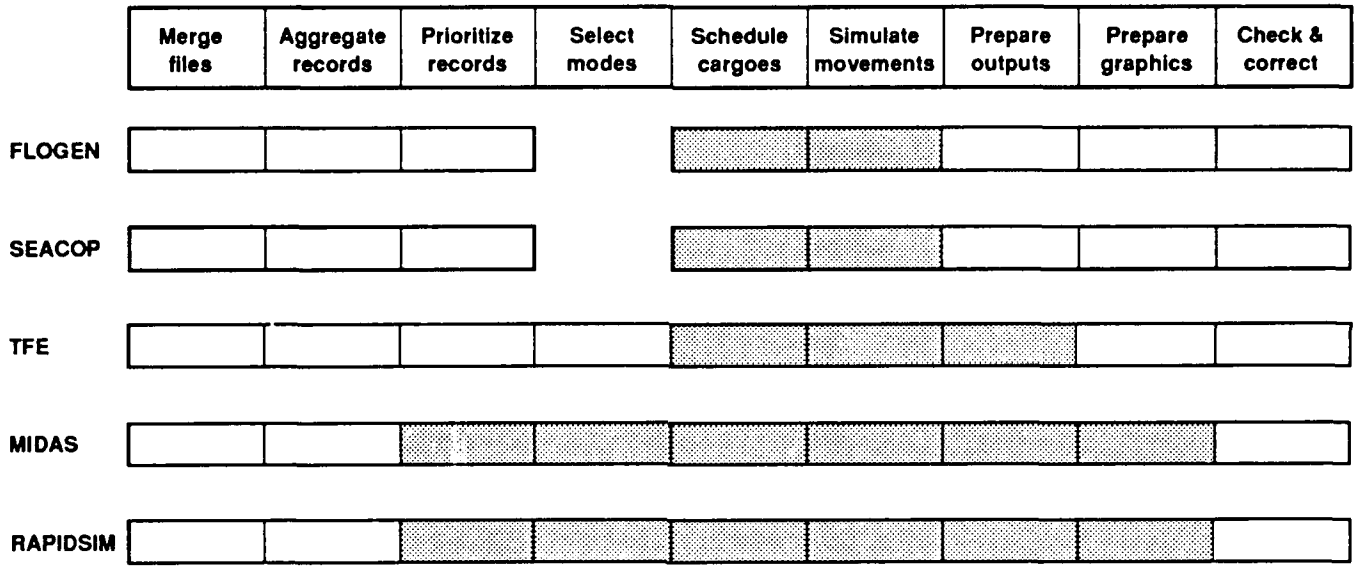

Fig. 7—Current models cover different groupings of tasks

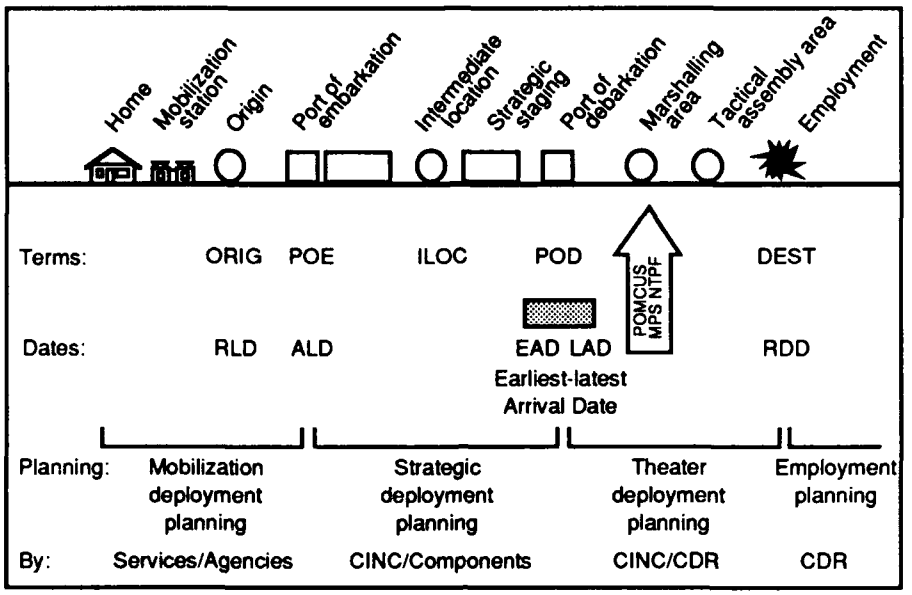

Fig. 8—Coverage: Strategic mobility—fort to foxhole

Although the strategic mobility problem runs from "fort to foxhole," the different models cover various spans of the journey (see Fig. 9). MIDAS, for example, covers movement through the complete system, whereas the other models generally cover only movement from the POE to the POD. In Fig. 9, the rows represent the various nodes and links of interest, ranging from Home to Destination; these directly correspond to the nodes and links shown in Fig. 8. The columns indicate the particular model. At the intersection of each row and column is either a blank or the word "factor" or "simulate." A blank indicates that the model does not cover this part of the problem. The word "factor" indicates that this particular node or link is modeled using a simple multiplication factor, addition factor, or flow calculation. For example, at the intersection of the column "MIDAS" and the row "Movement to POE" is the word "factor," because MIDAS models movement to the POE by dividing CONUS into ten or more regions, and it gives all cargo that originates within a particular region the same travel time (a "factor") to the POE. The word "simulate" indicates that a more elaborate modeling technique is used, such as discrete event simulation or calculation based on a queuing theory.

	MIDAS	RAPIDSIM	TFE	SEACOP	FLOGEN
Home to POE					
Origin					
Movement to POE	factor				
POE					
Sealift					
POE berthing	simulate	factor		factor	
POE loading	factor	factor		factor	
Movement to convoy point	simulate	simulate			
Convoy assembly	simulate	simulate			
Movement to POD	simulate	simulate	simulate	simulate	
POD berthing	simulate	factor		factor	
POD unloading	factor	factor		factor	
Airlift					
POE berthing/ferry	factor				factor
POE loading	factor	factor			factor
Movement to POD	factor	factor	factor		simulate
POD ground operations	factor				factor
POD unloading	factor	factor			factor
Movement to recovery area					factor
Recovery ground operations					factor
Recovery					factor
POD to destination					
Movement to marshalling area	factor				
Marshalling (POMCUS, MPS, NTPF)	factor				
Movement to destination	factor				

Fig. 9—Coverage: Nodes and links

Another difference among models is the depth of detail they cover. For example, although MIDAS covers the greatest span, from origin to destination, two other models with less breadth provide considerably greater depth of detail. SEACOP deals only with sealift, and FLOGEN only with airlift, but they model their modes in such great detail—for example, they each model many individual POEs and PODs, whereas MIDAS typically models three very aggregate POEs and only one or

two PODs[5]—that their runtimes are generally an order of magnitude greater than the other models' runtimes.

Solution Characteristics

All five of the current models are deterministic simulations. Therefore, none claims to compute an overall optimum solution; instead, they schedule and simulate "day" by "day."

Each model assigns priorities to cargoes in an inflexible priority order. There is therefore no provision for tradeoffs between lateness of different cargoes of the same priority; they do not determine the relative value of cargo A or cargo B being late. Nor is there any treatment of dependencies between various cargoes. For example, if a combat force is going to be late, there is no provision for revising the required delivery date for its support. Furthermore, the models always choose the fastest available vehicle and attempt to fill vehicles completely.

Figure 10 shows the data by which the cargoes are ranked. All models assign priorities to cargoes based on CINC's desired delivery sequence. All target either latest arrival date (LAD) or required

Priority	MIDAS	RAPIDSIM	TFE	SEACOP	FLOGEN
First	RDD-time[a]	LAD	LAD	LAD-time[a]	LAD-time[a]
Second	RLD	ALD	Channel		
Third			CINC's priority		
Fourth			Priority add-on		
Option[b]					CINC's priority

[a] Time stands for loading, travelling, and unloading time. MIDAS, SEACOP, and FLOGEN compute an "estimated (latest possible) shipping date." MIDAS subtracts its estimated travel and load time from the RDD; SEACOP and FLOGEN subtract the estimated travel time from the LAD.

[b] TFE normally incorporates the CINC's priority and the CINC's priority add-on as sort variables; FLOGEN uses the CINC's priority as an alternative to LAD-time occasionally.

Fig. 10—Solution characteristics: Assigning priorities to cargoes

[5] MIDAS has the ability to model up to 46 APOEs and APODs and 39 SPOEs and SPODs. More aggregate "port complexes" or "centroids" are used to reduce model runtimes.

delivery date (RDD); and FLOGEN, MIDAS, and SEACOP consider loading/transit/unloading time in addition to LAD/RDD. MIDAS uses RDD because it gives the required date for delivery to the destination and MIDAS covers delivery to the destination; RAPIDSIM uses LAD because LAD is the required date for delivery to the POD, which is the final node of RAPIDSIM models. In practice this difference is very small since LAD and RDD tend to be highly correlated; RDD is equal to LAD plus intratheater travel time.

One difference in solution characteristics is the selection of the mode of transportation: MIDAS and RAPIDSIM can select modes; with TFE all the cargo is "pre-moded"; SEACOP and FLOGEN consider only one mode. SEACOP allows multiporting, but the other models only work "point to point."

Cost in Time

Both the time it takes to run a model and the time it takes to prepare for a model run directly affect the cost of an analysis. Since a model may be run hundreds of times for a given analysis, small differences in runtimes may mount up quickly. Figure 11 shows the relative runtimes of the models. The vertical axis shows the CPU hours spent in calculation. The runtimes are given for a "typical" European

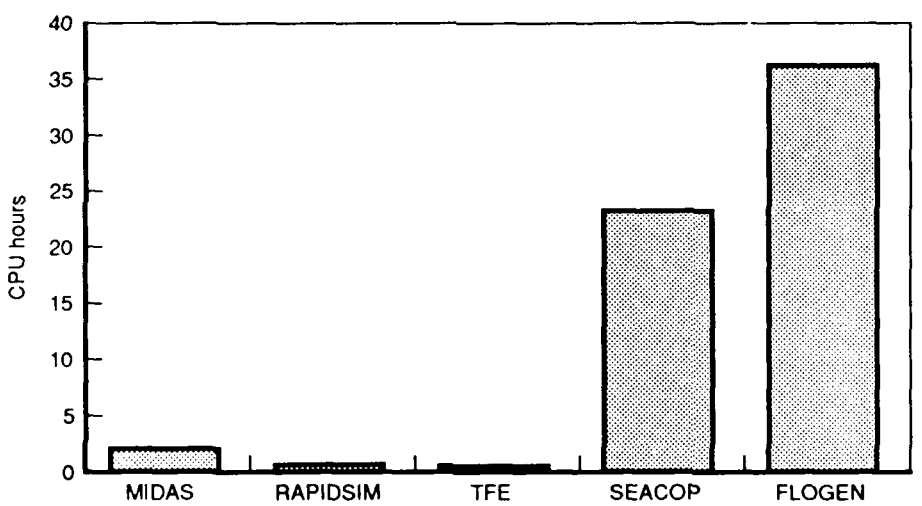

Fig. 11—Cost: Runtimes for 4102/DPQ

scenario run on each model. Since the scenarios are not identical across models, these numbers are not precise, but the overall result warrants attention: There is an order of magnitude difference in the runtimes of MIDAS, RAPIDSIM, and TFE versus FLOGEN and SEACOP. The first three models take only a few hours to run, whereas the very detailed, albeit single mode FLOGEN and SEACOP runs can take a day or more.

Runtime is only a minor portion of the total analysis time. The vast majority of time is spent in data preparation and management: data collection, correction, debugging, and massaging. Data preparation can take weeks or months, as illustrated by Fig. 12. Data management cost is *the major cost* for strategic mobility analysis.

MODELS UNDER DEVELOPMENT[6]

The next generation of strategic mobility models is already being developed, though not all users in the defense community have new

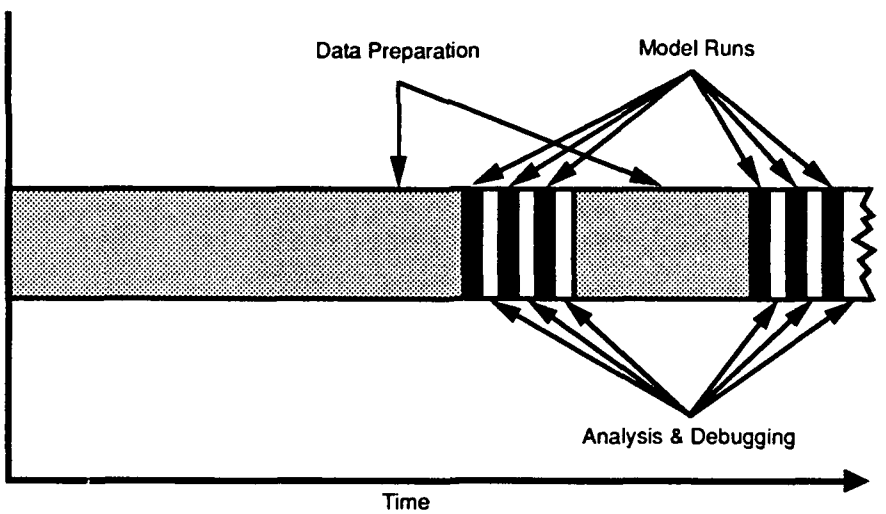

Fig. 12—Data management dominates costs of strategic mobility modeling timeline

[6]For most of the models in this section, specifications and solution techniques are not fully defined at this time. The information contained in this section is current as of the summer of 1990, but because the models are evolving with the prototyping efforts, our information may be rapidly outdated as the models are revised, or even scrapped.

models under development. Four of the new models are being developed at Oak Ridge National Laboratories (ORNL), which will probably play the same pivotal role for this generation of models that General Research Corporation played in the development of the previous generation. All of the new models we examined will run on microcomputers or workstations, with mainframes relegated to being merely large database servers.

Another characteristic about the next generation of mobility models is that they are geared toward deliberate and execution planning, rather than to resource planning. This fact is of particular importance to the JS/J-4, which primarily conducts resource planning.

Figure 13 shows the new generation of models: ADANS, SEASTRAT/SAIL, STRADS, FAST, GDAS, and ARM. The rows of the figure show the potential users of new strategic mobility models, and the columns show the uses for strategic mobility models.

	Resource Planning	Deliberate Planning	Crisis Action Planning
OSD			
Joint Staff			
Service HQs	GDAS		
CINCs			
Service components			
TRANSCOM MAC MSC MTMC		FAST ADANS SEASTRAT STRADS	FAST ADANS SEASTRAT STRADS
Combined commands	ARM		

Fig. 13—Next generation of strategic mobility models

ADANS

The Airlift Deployment Analysis System (ADANS) will replace FLOGEN as the primary planning, scheduling, and analysis tool for MAC. ADANS is being developed at ORNL and will use two different algorithms, one for deliberate planning and one for execution planning. The deliberate planning algorithm is a "greedy heuristic"—an algorithm that processes requirements in the order that produces the most immediate benefit. The execution planning algorithm is an "insertion heuristic"—an algorithm that takes an existing schedule (possibly an empty one) and adds or deletes one requirement at a time in some "optimal" fashion. ADANS will run on a network of SUN/4 workstations. Final delivery of the model is scheduled for the fourth quarter of fiscal year 1992.

SEASTRAT/SAIL

The Strategic Sealift Planning System (SEASTRAT) will replace SEACOP as the deliberate and execution planning scheduler for MSC. SEASTRAT development is being overseen by NARDAC, and ORNL is developing the scheduling algorithm, which is called Scheduling Algorithm for Improving Lift (SAIL). SAIL divides the rather difficult sealift scheduling problem into two more manageable portions: (1) development of ship schedules, using conventional transportation network techniques and heuristic decision rules; and (2) assignment of cargoes to ships using heuristics. (This approach of splitting the transportation problem into routing and cargo assignment is the same one that MODES used; but MODES used linear programming techniques, whereas SAIL uses heuristics.)

SAIL was originally designed to be run on an IBM 3090 mainframe at NARDAC, using linear programming to solve the routing problem. However, the new heuristics technique is so fast that SAIL can now be run on a high-end PC.

STRADS

The Strategic Deployment System (STRADS), which is the third in the ORNL line, is to replace MAPS-II as MTMC's scheduler. At the heart of the current prototype of STRADS is a conventional commercial network LP solver. The solver is encapsulated in a user-friendly microcomputer database and report system. The current prototype runs on a high-end PC running MS-DOS. The final product may reside either on a microcomputer or a mainframe.

FAST

The Flow and Analysis System (FAST), also by ORNL, is being developed for USTRANSCOM. It uses algorithms from STRADS, the MAC-Planner's Toolkit, and SAIL to simulate CONUS movement, airlift, and sealift, but it has no mode selection capability. FAST encapsulates these algorithms in a user-friendly application that preprocesses and post-processes movement data. FAST currently requires an 80386 or higher-class PC running MS-DOS with 16 megabytes of memory to run the sealift subsystem; the air and land subsystems require only 640K of memory.

GDAS

The Global Deployment Analysis System (GDAS) is under development by Stanley Associates, Inc. and Noetics Inc. for CAA. It is the first stage of a system to evaluate mobilization and deployment systems of the Department of Defense and to provide input to CAA combat models. GDAS features a user-defined objective function—the analyst can vary key parameters to reflect his priorities. Even though GDAS explicitly defines an objective function, it uses heuristic techniques instead of linear programming. GDAS will run on either a high-end PC or a Sun workstation.

ARM

The Ace Reinforcement Model (ARM) is under development at and will be used by the SHAPE Technical Center to study rapid reinforcement. It uses conventional discrete event simulation techniques. ACE is written in Turbo Pascal and runs on a high-end PC.

IV. LIMITATIONS OF CURRENT AND EMERGING MODELS

In the previous two sections, we have described the users of strategic mobility models, the analysis questions those organizations address, the models they use to support the analysis objectives, and the models being developed for future mobility analysis. In this section, we discuss the limitations of the current models and the models under development; our main emphasis is on the models currently being used. We do not directly address whether or not the current models are operating correctly; in fact, one of our observations is that current models have not been thoroughly validated, and therefore it is almost impossible to tell if they produce results that would mirror actual wartime transportation operations. Instead, we describe the models' limitations in assisting analysts to address various mobiliity questions.

The focus of our research is on SCAD's analytical needs in the strategic mobility area. SCAD performs two general types of mobility studies—transportation requirements determination and capability assessments. As described in Sec. II, requirements studies address the quantity and types of movement assets needed to attain various desired force closures, and the tradeoffs that exist among airlift, sealift, and prepositioning. Capability assessments evaluate the potential of a given set of transportation assets and prepositioning to meet scenario defined sets of movement requirements. Both of these types of mobility studies fall under our category of resource planning analyses (the first column of Fig. 3).

Organizations other than SCAD are also involved in resource planning studies, and the limitations we see with current models apply as well to those organizations and the models they use. Furthermore, several of the models' shortcomings are not unique to resource planning needs; they occur also in deliberate planning and crisis action planning analyses.

WHAT MAKES A MODEL A VALUABLE ANALYSIS TOOL?

To be a valuable and productive tool for analysts, a model must be both credible and useful, implying several contributing attributes. Of primary importance to credibility is that the model be *correct* or *valid*; that is, the model must adequately represent the real world system it is

portraying. Analysts must develop an acceptable level of confidence that inferences drawn from the performance of the model are correct and applicable to the real world system.[1]

A related attribute is model *transparency*, or the ability to understand how the model "works." Understanding how a model works and having confidence that the model adequately represents the real world system are important requirements for any model. Although not a necessary condition for being a useful tool (few may understand exactly how a computer works, but it is still a valuable tool), understanding a model's processes and operations increases user confidence and fosters a better understanding of the appropriate, and inappropriate, uses of the model. Credibility is important not only for the organization using the model, but also for organizations asked to make decisions based on the output of the model or to implement the recommendations resulting from the analysis.

Usefulness also requires a number of contributing attributes. Models should be *responsive* to the needs and problems of the analyst and should directly address the question of interest. A model may be a very useful tool for a certain analysis objective, but may be inappropriate and inadequate for other questions (a screwdriver is a very useful tool for certain objectives, but has little value for driving nails). Furthermore, a model should provide measures to help the analyst understand sensitivities in parameters or variables. If a model provides only limited results, analysts are forced to make numerous trial-and-error changes in input values to understand the robustness of a solution, the value of additional assets, or the cost of fewer assets.

Model usefulness can also be increased by making a model more *flexible*. Model flexibility can relate to the range of questions the model can address (a more flexible tool is one that has more uses), or to the range of input data values the model can accept and process. In this latter regard, mobility models are flexible tools for analysts if different degrees of data detail and accuracy can be used in the analysis process.

Finally, models should be *easy to use*. Models that are difficult to learn how to use, cumbersome to operate, or time-consuming to prepare or execute will have less value, and potentially less use, than models that are easy to learn, easy to use, and quick to run. Transparency helps make a model easy to use, and it especially helps make a model easy to modify and update.

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[1]Model validity is not an either/or condition, but rather should be considered one of degree. Greater fidelity with the real world system is achieved with greater development cost and effort. Increased fidelity usually provides increased value to a decisionmaker, but typically at a decreasing rate. The model development process must consider the tradeoffs among cost, validity, and usefulness.

LIMITATIONS OF CURRENT MODELS

Based on the preceding criteria, the current mobility models exhibit the following limitations:

- They lack credibility among subcommunities:
  - — No single model is accepted, or used, by more than a few organizations.
  - — Few people understand exactly how any of the models "work."
  - — None of the models has been adequately validated.
- They are not sufficiently useful:
  - — They all work in one direction only, accepting similar types of input data and producing the same general information.
  - — They do not recognize or incorporate the various uncertainties that characterize war, and they provide few, if any, measures of sensitivity or robustness.
  - — Their narrow objective functions do not consider either the linkages or the possible tradeoffs between cargoes.
  - — Their output measures do not adequately serve analysts' needs.

In addition to the model limitations, there are also several shortcomings with the pre- and post-processing steps that surround all models.

Current Models Have Little Credibility

A major problem we observed with the current suite of mobility models is that no one model is generally accepted throughout the community. Few users understand how other organizations' models "work," and because current models have been subjected to only minor validation procedures at best, few users have confidence that the models are producing accurate answers.

The models developed to represent the strategic mobility system are very complex, in large part because the system itself is complex, involving numerous interacting organizations and events. However, users would be able to understand even complex models if those models were well constructed and if adequate documentation were available. This is not the case with the existing models. First, most of the current models were developed 15 to 20 years ago. They use dated hardware, software, and algorithmic technologies, and they have been patched or modified to the point where it is difficult, if not impossible, to under-

stand how they produce their results or to verify if they are operating correctly. Some models have been modified to such an extent that their using organizations no longer have confidence in them and feel compelled to develop new models.

Second, the existing models are not "transparent"; that is, one cannot easily "read" the model code to understand the logic flow and processes. When documentation exists, it often provides little assistance in understanding model decision logic, structures, and procedures.

These problems lead most analysts to view the models as "black boxes." The overall lack of understanding of model solution procedures often results in mobility analysts needing the model builders to actually run the models and to explain the types of analysis questions the model can support. This dependency on the model builders limits and constrains analysts and often impedes the analysis process.

Model users can still feel comfortable using a model, even if they do not understand how it works, if they are confident that the model is adequately representing the real world system. Current models, however, have been subjected to few validation procedures; at least we found few citations of attempts to validate models or to compare the results with real world data.[2] In a few instances, area "experts" have reviewed selected portions of a model. Also, there have been attempts to compare one model's results with those of another. However, the results of such checks and comparisons often lead to more questions than are answered. As a result of this lack of thorough validation, model users often question whether the model is providing "correct" answers or is representing the mobility system with adequate fidelity.

Although analysts appear not to completely understand the model they use, they understand far less about other mobility models. Therefore, model advocacy is typically based on the "familiarity" an organization gains through using a model. In some cases, models become accepted because they were used in studies whose results were accepted in the community. But typically, the general lack of model credibility results in organizations questioning the results of studies performed using models other than their own.

[2]Numerous organizations are closely monitoring the transportation aspects of Operation Desert Shield. The insights gained from this major deployment of forces, equipment, and resupply should provide invaluable assistance in "calibrating" the major mobility models.

Current Models All Work in One Direction

All the major current mobility models are simulations or have major simulation components. As described in Sec. III, they all accept data on what has to be moved (cargoes), what is prepositioned (PREPO), what transportation assets are available, and what the assumptions are regarding timing and available infrastructure. They then assign cargoes to transportation assets according to specific rules and simulate their movement through the transportation system. Finally, they all produce estimates of when units are delivered into the theater and measures of the utilization of the transportation assets and facilities (see Fig. 5).[3]

All existing models use this process, regardless of the decisions and objectives being addressed. All the models basically answer one question:

> "What is the closure profile for these forces, support units, and resupply given these transportation assets?"

This question may be appropriate for deliberate planning or execution planning analyses, but it does not directly address the concerns of *how many* transportation assets *are required*, the question raised during resource requirements studies.

Strategic mobility analyses that address transportation asset requirements ask the following question:

> "What is the best mix of transporation assets for achieving a desired closure profile for a given set of forces, support units, and resupply?"

This is very different from the question that existing mobility models answer directly. In fact, the very values that are unknown in requirements determination are required inputs to existing models.

At present, therefore, analysts cannot directly answer the question of how many of each type of transportation assets is required; they can only approximate the solution by multiple runs and trial and error. Figure 14 provides a representation of how analysts must use current models when performing requirements determination studies. The hundreds of runs of the MIDAS model for RIMS is an example of how current models must be manipulated to approximate answers to resource requirements questions.

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[3]We use the term "direction" to relate what a model accepts as input and what it produces as output. According to our terminology, current models work in a *forward* direction; that is, they take a set of starting conditions and estimate the end result. We believe requirements determination studies need a model that works *backward*, or takes the desired goal (closure profile) and estimates the starting conditions needed to meet that goal.

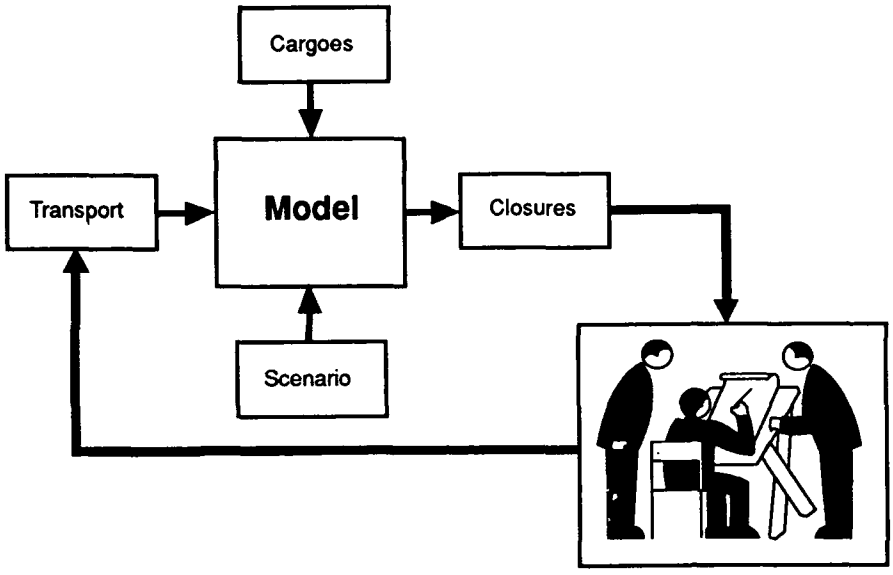

Fig. 14—Requirements determination takes many iterations

This laborious process, more art than science, certainly does not provide "optimal" answers. In fact, a good deal of expertise is typically needed to develop even a "good" answer to transportation force structure issues. This suggests a different modeling approach is warranted, one that moves away from simulations, or at least from current simulation methods, to an approach that directly addresses force requirements questions.[4]

This new model would reverse some of the input and output flows of current models (see Fig. 15). For requirements determination

[4]The solution technique used by all the current mobility models, deterministic simulation, is not the only technique available for solving strategic mobility problems. In the past, mathematical programming (MP) techniques have also been used. The most recent notable example is the Mode Optimization and Delivery Estimate System (MODES), a model based on MP techniques developed at Georgia Tech. MODES did not gain wide acceptance because it did not model the transportation system in an intuitive fashion (for example, it modeled ship and airplane movements as steady state channel capacities). In addition, the computer platform used proved to be a poor choice for development and operation of a large scale model. Because of these problems MODES development was discontinued in 1987; however, some of the techniques in MODES have been incorporated in the next generation of strategic mobility models currently under development at ORNL.

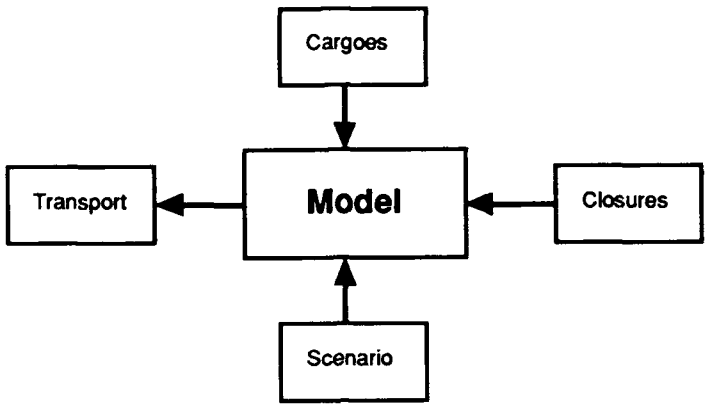

Fig. 15—New type of model is needed to directly estimate lift requirements

questions, the desired closure profile would be an input, and the required transportation assets would be an output. Such a model could directly answer questions concerning the best mix of transport.

A model that works in a different direction from current models (or, in the best of situations, could work in both directions) is not a totally new concept for strategic mobility analysis. Mobility models developed 30 years ago during the McNamara era attempted to directly address transportation requirements. Those models typically used linear programming formulations to solve the problem. However, because of hardware, software, and algorithm limitations, the models often fell short of desired objectives.

Because of the problems with the linear programming formulations and because the emphasis was shifting from requirements to capabilities, simulation approaches were adopted for strategic mobility questions. The Transportation Feasibility Estimator (TFE) was developed in the early 1970s to help theater commanders put together transportationally feasible plans. TFE used simulation to estimate closure profiles. The models that followed, most notably the ancestors of RAPID-SIM and MIDAS, also addressed force closure questions using simulation approaches.

Recent advances in technology, primarily in the hardware and algorithm area, offer renewed promise for mathematical programming formulations. Faster processors, inexpensive storage, and new approaches to solving linear and integer programming problems suggest it may be an opportune time to consider a model that moves away from simulation and back to closed-form analytical formulations. Such a model could not only directly answer the question of how many ships and airplanes are needed, but could also provide an "optimal" answer to the question along with various sensitivity measures.[5]

In addition, recent knowledge-based modeling techniques developed in artificial intelligence allow building models that can be used in *either* direction. A single knowledge-based model can work *forward* to perform simulation or *backward* to answer goal-oriented questions or generate plans for achieving a desired result. The answers derived from a single bidirectional model of this kind are necessarily consistent, which is not the case for different models working in opposite directions. Furthermore, since a knowledge-based model represents a domain in terms of knowledge that is both directly comprehensible to users and fairly independent of the specific use to which it will be put, it can answer a broad range of unanticipated questions without the need for recoding or reformulation. Finally, artificial intelligence techniques for representing and reasoning about uncertainty should allow building models that deal with the inherent indeterminacy of strategic mobility. Knowledge-based modeling therefore appears to hold great promise for producing mobility models that are both more comprehensible and more flexible than traditional simulations or mathematical programming models.

Current Models Fail To Incorporate the Uncertainties of War

A third shortcoming we perceive with current models is that they all assume everything is known with certainty, though of course wartime will be characterized by numerous uncertainties. During wartime, analysts cannot be sure of the quantities of equipment and personnel that units actually possess, the availability and performance of transportation assets, or the availability and capability of airfields and ports. Also, enemy actions or political situations may give rise to events that are unanticipated during peacetime planning. A theater commander's plans and tactics may therefore change, resulting in changes to deployment plans.

[5]The potential application of linear programming to the resource requirements problem is discussed in more detail in App. C.

None of the current mobility models recognizes or incorporates these numerous uncertainties. The answers that result, whether they are force structures or deployment plans, may "work" for only a very narrow set of events that may unfold in a war. If the actual situation in wartime deviates from that set, the force structures and plans may no longer be adequate.

This problem is particularly acute for long-range requirements determination studies. When addressing questions of whether to obtain a particular type of transportation asset (e.g., should the C-17 be procured?) or how many to obtain, analysts must make estimates of future force structures and operational objectives. Because of the long lead times, these estimates are, at best, knowledgeable guesses. The existing mobility models take these estimates and produce single point answers. If analysts are interested in the effect of perturbations, they must change input values or model parameters and rerun the model. This trial-and-error approach to understanding the effect of uncertainties is time consuming and can cause problems in interpreting the results of the various model runs. Also, the multiple model runs may not provide a true measure of how robust[6] a particular set of transportation assets is.

Wartime uncertainties also affect deliberate planning studies. Although not necessarily looking as far into the future as requirements determination studies, deliberate planning analyses consider potential future hostilities. Analysts again must make assumptions about enemy actions; performance of units, weapon systems, and munitions; and the degree of support provided by U.S. allies. The resulting operational plans are used with the mobility models to develop a transportation movement schedule. If the actual circumstances during a war unfold in a manner different from the planning assumptions, the movement schedules must be changed at the last minute or the mobility system will not deliver the right units to the right places at the right times.

We believe that mobility models should produce robust solutions, or at least help the analyst to understand the range of scenarios and assumptions for which a solution "works." What must be avoided are transportation force structures that are optimal for only one or a few possible wartime scenarios and set of events, but fall apart quickly if actual events deviate from that narrow set of events.

[6]By a *robust* solution, we mean a set of transportation assets or a deployment plan that "satisfies" or "works" for a range of planning assumptions or scenarios.

Objective Functions Are Too Narrow and Rigid

As we have mentioned previously, all the models we examined are simulations that use heuristic rules to assign cargoes to transportation vehicles and then track the movement of the cargoes and vehicles through the system. The "objective functions" that drive these models are represented by a model's cargo assignment rules. We believe these objective functions are too narrow and rigid and often fail to reflect a commander's true preferences for alternative delivery options.

As described in Sec. III, all models use basically a two-step procedure to assign cargoes to vehicles. The first step orders or prioritizes cargoes based on some measure of desired delivery time. The second step then takes each cargo in priority order and schedules it on the "best" lift vehicle available.

The problem with the first step is that the delivery dates used to order the cargoes are often changed rather arbitrarily. The process begins with the CINC specifying his desired delivery profile for the various combat and support forces. Since there is usually not enough lift to meet the desired delivery profile, the delivery dates are modified, first by the theater service components and then by the transportation operators. The CINC is represented at conferences discussing the changes, but usually the changes are handled individually without considering the interrelationships among combat units, support units, and the necessary resupply. The resulting "desired" unit arrival dates are then used to set the priority order for cargoes and, therefore, to drive the models.

There are also problems with the second step of assigning cargoes to lift assets. The nature of the rules used for this assignment often results in models being classified as either "min-time" or "min-cost." Some models' assignment rules are driven rigidly by the desired delivery dates ("min-time" models), resulting in some transportation assets (most often ships) leaving with only partial loads. Other models' assignment rules are driven by efficiency measures ("min-cost" models), resulting in transportation assets always leaving fully loaded, but cargoes arriving later than desired.

In reality, both minimizing unit lateness and maximizing transportation asset utilization are important measures. But these are not the only metrics that should drive the mobility system. The theater commander has preferences for the sequence of cargo arrivals, preferences he indicated through his original desired delivery dates. As these initial values are modified during the deliberate planning process, the commander's priorities get lost or modified. The end result may be a delivery profile for forces that meets one type of objective but falls

short for other objectives. The complexity of the mobility system and the wide range of decisionmakers involved suggest that a model's objectives should be broader than just time or cost.[7]

A second problem is that there is typically no consideration of the interrelationships among different cargoes. If the delivery of a cargo is slipped because suitable transportation assets are not available, few models investigate whether other cargoes may also be affected.[8] For example, if a combat unit is delivered two days late, it may be possible also to slip the delivery of the support and resupply requirements tied to the combat unit.

The end result of the narrow objective functions in current models may be a less than optimal delivery schedule or an inefficient utilization of transportation assets. One manager in the system may have his objectives met, while the preferences of other managers are ignored. Cargoes may be scheduled in a way that minimizes their average or total lateness, but cargoes important to the theater commander may be delayed in the process. Combat units may arrive on time, but their needed support and resupply may be delayed, diminishing the capability of the combat unit. Or the support and resupply may be delivered before the associated combat unit arrives. Attempting to rigidly meet artificial desired delivery dates may result in more transportation assets required (and, therefore, higher costs) than are really needed to meet a commander's objectives.

Existing Models Produce Limited Output Measures

A final problem we perceive with current models is that their output measures are not sufficiently helpful to decisionmakers. All current models provide force closure profiles (delivery dates) and measures of the utilization of transportation assets and facilities. However, these measures do not explain the *operational effect* of alternative mobility plans or delivery options. It is one thing to know that a unit arrives later than planned; it is more important to the commander to know the value—in casualties, ground lost, or objectives not achieved—of the unit's late arrival.

More meaningful output measures are particularly important for requirements determination studies. These studies deal with large numbers of aircraft and ships, which typically are very costly. A model may indicate that one fewer ship will result in several units being

[7]In fact, none of the current mobility models actually "optimizes" a "min-time," "min-cost," or "max-efficiency" objective function. At best these models suboptimize for each day's cargo.

[8]MIDAS seems to handle resupply in an intelligent fashion.

delivered slightly later than planned. Ideally, the analyst should know if these later delivery dates have an impact on operations. If they do, the cost for an additional ship may be warranted; if there is no effect or very minimum effect on operations, the additional ship may not be needed, and money can be saved.

If mobility models produced information on the combat value of alternative delivery options, decisionmakers would be better informed about the value of different force closure profiles. We realize, however, that programming a single model to provide this information would be an extremely difficult task. A more practical approach may be to integrate a mobility model with a combat-oriented model. By properly interfacing the two models, the combat effects of different closure profiles could be determined.[9]

PRE- AND POST-PROCESSING FUNCTIONS OFTEN HINDER MOBILITY ANALYSIS

In addition to examining the models, we also investigated the overall analysis process. Before a mobility model can be run, there are several pre-processing steps including developing, checking, and aggregating the necessary input data. After a model is run, there are several post-processing functions including checking, correcting, disaggregating, and displaying the model results. These functions typically consume the majority of the analysis effort. Although model runs may take only a few hours, the overall analysis process takes many weeks and man-months of effort.

Pre- and post-processing functions hinder and constrain mobility analysts in many ways. Analysts, especially at the JS/J-4, must rely on other organizations to provide data on movement requirements or transportation assets, particularly for the support tail tied to combat units. The support and resupply needed for those combat units currently can be identified only by the specific services. In some cases, for example the Army, identifying support requirements may be a very detailed and time consuming process, resulting in the mobility analysts depending on outside organizations and an overall delay in the analysis process.

Another problem is with aggregation. A large operational plan may have up to a hundred thousand individual movement records (cargoes), which must somehow be aggregated to ten thousand or fewer for the models to execute in reasonable times. Mobility analysts, because of

[9]This technique has been utilized in the past through the integration of the MIDAS and TACWAR models. Also, RAPIDSIM has been used for various wargames to simulate the mobility system and to provide resulting inputs to a combat model.

their lack of understanding of how their mobility model works, often must rely on the model developers to organize and aggregate the input data. For example, there are General Research Corporation (GRC) analysts assigned to both the JS and to OSD(PA&E) for the sole purpose of running the MIDAS model. As a result, the mobility analyst feels isolated from the analysis process, further contributing to doubts concerning the overall credibility of analysis results and recommendations.

A third difficulty is that all the models produce vast amounts of output on when units arrive in the theater and how assets and facilities are utilized, and this output information is typically not organized in ways meaningful to decisionmakers. Someone must pour through the reams of output, checking for errors and consistency, disaggregating the units that were grouped together in the pre-processing steps, and organizing and displaying the results in meaningful ways. These post-processing steps are very time consuming and often require the assistance of other organizations, typically the model developers. Again, the mobility analyst is somewhat isolated from the analysis and often does not fully understand the implications of the results produced by the models.

LIMITATIONS OF MODELS CURRENTLY UNDER DEVELOPMENT

Several models are now being developed by various organizations to assist in strategic mobility analysis. Although some of the features of these emerging models are expected to help overcome limitations of existing models, we believe the new models still will not adequately address all of the issues enumerated above. In particular, the new models do not appear to address the issue of wartime uncertainties, they use objective functions that differ little from the existing models, and they do not produce operationally oriented output measures.

An even larger concern from the Joint Staff's perspective is that this next generation of mobility models—however well or poorly they perform for the organization procuring them—will not be appropriate for the kind of analysis and planning SCAD performs. Like the old models, the new models are being designed to address deliberate and crisis action planning questions, not requirements determination issues.

Given the limitations of both current and emerging models—especially in regard to resource requirements issues—and the limitations of the overall analysis process, we recommend that the JS/J-4 develop a new model. The details of this recommendation are outlined in the next section.

V. A RECOMMENDED STRATEGY FOR THE JOINT STAFF

The problems experienced by SCAD with the MIDAS model during the RIMS led to the question of how the JS/J-4 could improve their mobility analysis environment. When we began our investigation, we enumerated four possible options for resolving the JS/J-4's problems with MIDAS. The Joint Staff could upgrade MIDAS, replace it with a modification of another existing mobility model, adopt one of the models currently under development, or develop a completely new model of its own. The limitations of existing models described in the previous section suggest that adopting another existing strategic mobility model is not the solution to their problems. Nor do we believe that any of the models currently being developed will satisfy SCAD's needs in resource planning. And for a number of reasons, we do not believe modifying any of the existing models will result in a fully adequate resource planning tool. By the process of elimination of alternatives, we are left with the option of developing a new model.

This section describes the rationale for developing a new model for the JS/J-4 to use in resource planning studies. We also present short-term and long-term objectives of a strategy for developing the new model and for enhancing the pre- and post-processing functions important to all mobility analysis. Although our focus is on the JS and on resource planning, several attributes of a new model would also be useful to other organizations and for deliberate and crisis action planning activities.

WHY THE JOINT STAFF NEEDS A NEW MOBILITY MODEL

All models have limitations, and no one model can address all the important questions in an area of interest. When models exist that cannot directly support the analysis concerns, those models are typically modified to provide the types of answers desired or to reflect changes in the modeled environment. This has been the normal practice for the existing mobility models, all of which have been in use for at least ten years. But continual model modifications lead to confusion about how the "patched" model produces solutions and to doubts concerning the validity of the model results. Both MAC and CAA have

reached this point with their respective models (FLOGEN and TRANSMO) and have decided to develop new models (ADANS and GDAS).

SCAD was forced into this model modification process during RIMS. Numerous programs and a substantial amount of computer code were developed to augment the MIDAS model. And these changes and enhancements further contributed to the opacity of the model and the uncertainty about the analysis results.

A bigger problem faced by SCAD is using a model for a purpose different from the one it was designed for. MIDAS and the other major mobility models were designed to produce force closure profiles for a given set of transportation assets. MIDAS addresses this specific question fairly well, at least as well as or better than the other available models. But resource requirements issues turn the question around, seeking the assets necessary to meet a desired closure. No matter how good the model, not using it in ways it was designed for often causes analysis problems.

Because of the problems that result when existing models are substantially modified, and because none of the existing models was designed to specifically address resource planning questions, we believe neither MIDAS nor another existing model could be profitably modified to meet the mobility analysis needs of the JS/J-4.

For similar reasons, we believe that the JS/J-4 should not adopt one of the new models being developed.[1] Those models are being designed to address deliberate and crisis action planning questions, not requirements determination issues. Furthermore, several of the new models are limited in scope; ADANS considers only airlift; SEASTRAT considers only sealift; and STRADS considers only intra-CONUS movements. Finally, we believe the models under development will not adequately address the issues presented in the previous section. For example, they do not address wartime uncertainties, they use objective functions that differ little from the existing models, and they do not produce operationally oriented output measures.

Needing a model that directly addresses resource requirements questions in a way that is transparent and easily understood is only one reason for the Joint Staff to acquire a new mobility model. A second

[1]Although none of the models currently being developed may be appropriate for the JS/J-4 use, there are features of those models that may prove helpful. Most of the new models, especially the STRADS model for MTMC, have impressive user interfaces effectively employing graphics and menu structures to assist users in identifying and assembling input data sets. Several of the new models also produce graphically oriented output. Finally, the new model being developed for CAA has several important database management features in its design specifications. These new capabilities should all be considered during the development of a new model for the JS/J-4.

reason is the whole new set of issues and concerns that is facing the Joint Staff and the Department of Defense. The existing mobility models were developed, and have been used almost exclusively, for strategic issues centered on a major war in Europe. Future mobility issues promise to be much more diverse and filled with greater uncertainties. Whether the existing models can adequately deal with these new issues is a question of growing concern.

The recent changes in the political environment of Eastern Europe, the apparent thawing of East-West tensions, the possible withdrawal of U.S. troops from Europe, and the potential downward swing in defense budgets all suggest that new types of mobility requirements questions will be raised. The ability to project forces into Europe will remain a major area of analysis but will take on a different flavor as our presence in Europe decreases and the warning, mobilization, and deployment windows increase. NATO scenarios will no longer be the focus of all mobility analyses and will no longer dictate the transportation assets the United States introduces and maintains in its force structure. Low intensity conflicts in Third World regions, with scenarios potentially involving simultaneous regional conflicts, will receive more and more attention.

To address the questions that surround the mobility aspects of LICs, the Joint Staff's models will need to be more flexible and to consider more generic types of force packages (movement requirements) and theater transportation support infrastructures than they ever have before. Models will have to assist in addressing a wider range of questions and "what-if" types of analyses and to provide answers quickly. And the models will have to help analysts understand the numerous uncertainties surrounding the conduct of low intensity conflicts. Current models provide little assistance in these areas.

Finally, we believe the Joint Staff should develop a new mobility model because of the advantages offered by new and emerging technologies. Current models are old and use dated hardware, software, and algorithm technologies. New algorithms for linear, nonlinear, and integer programming problems have been developed that allow models to capture more of a system's complexity or to produce answers more quickly. New computer hardware, such as parallel processors or special purpose machines, also offer greater model fidelity and quicker turnaround times. Advances in software engineering and in software languages, such as object-oriented programming, can improve the transparency of models and explain why and how a model produced certain answers. Finally, advances in simulation technology, such as the knowledge-based modeling work evolving from research in artificial intelligence, can help analysts address more varied mobility questions.

Our main recommendation, therefore, is that the Joint Staff begin the development of a new mobility model, one that uses the new technologies to directly address resource requirements questions. Developing new models, however, takes time, and the Joint Staff will continue to face resource requirements questions in the interim. While pursuing the long-range objective of developing a new model, we recommend that the Joint Staff continue to use MIDAS and RAPIDSIM. However, they should begin immediately to improve the pre- and post-processing functions that are necessary regardless of the model being used.

SHORT-TERM ELEMENTS OF THE RECOMMENDED STRATEGY

Continue to Use MIDAS and RAPIDSIM

We believe the JS/J-4 should continue to use MIDAS and RAPIDSIM in the near term because these models are comparable to the others we examined and offer some advantages. For example, MIDAS is the only model we have seen that considers the entire mobility system, from "fort to foxhole." It also incorporates the most detail, modeling phases of the process that are treated with factors in other models. Furthermore, both MIDAS and RAPIDSIM include travel time when ordering cargoes and have a mode selection capability. Most important, the JS/J-4 has gained familiarity and a degree of acceptance with the models, having used them in numerous studies.

Improve Pre- and Post-Processing to Speed Analysis

A positive step the JS/J-4 can take in the short term is to improve the pre- and post-processing functions, which are independent of the actual model used. These functions include developing the movement requirements data; checking, sorting, and aggregating all the input data; and checking, correcting, disaggregating, and displaying model results. These functions currently consume the majority of the analysis time and effort.

To improve the pre- and post-processing functions, we recommend that new routines, potentially expert systems, be developed to generate movement requirements, to check input data for errors and for consistency, and to aggregate cargo records. These routines should be "standardized" so they are compatible with both current and future

models. A commercial database management package should be procured to assist in organizing and manipulating the data, and a commercial graphics package should be obtained to summarize and display model outputs in ways that are meaningful to decisionmakers.[2]

An example of a routine that would be of value to mobility analysts is the development of the support and resupply needed for a combat force. Currently, such information must be provided by the services, a process that often takes a substantial amount of time from the initial request for the data to the actual receipt of the needed information. However, each service has a set of factors or rules that could be used to provide an initial estimate of support requirements.[3] Also, input data sets used for previous mobility analyses could be examined to develop additional rules. With such a routine, a mobility analyst could quickly estimate the support tail tied to a specific set of combat units.

The development of new pre- and post-processing routines should take advantage of the technology evolving from the widespread use of microcomputers. Many microcomputer application software packages use graphic interfaces and "user-friendly" menu structures to assist people using the package. The ORNL has adopted many of these techniques for the new models they are building. Again, some of these interfaces may map directly into the JS/J-4 analysis environment.

LONG-TERM ELEMENTS OF THE RECOMMENDED STRATEGY

The long-range objective of our strategy is the development of a new mobility model. This new model will not be an "improved" version of an existing model, but will embody new approaches that overcome the limitations of current models. This new model will be designed specifically to address resource planning questions and will result from a well-conceived development process. The development process is crucial. It must ensure that the resulting model will:

- Have widespread credibility.
- Have an objective function or functions that more closely represent warfighters' preferences and tradeoffs in the delivery of forces.

[2]The Joint Operational Graphics System (JOGS), available through JOPS, may also be an alternative.

[3]For example, the Army publishes *Staff Officers' Field Manual: Organizational, Technical, and Logistic Data*, FM-101-10-1, which contains factors for support and resupply.

- Contain methods for representing and incorporating the uncertainties that are inherent in war.

After the development process has determined the required functional characteristics of the new model, we recommend two parallel prototyping efforts be undertaken, one pursuing a mathematical programming model and the other using a knowledge-based modeling approach. These coordinated prototype efforts may ultimately be merged to provide a single analysis environment that would combine the strengths of each approach.

Validate the Model as It Is Being Developed to Ensure Credibility

We believe it is especially important that a new model have credibility throughout the mobility analysis community. Belief in and acceptance of the model are necessary if solutions and recommendations resulting from the model are to be implemented.

Strategic mobility is a complex process requiring complex models. Validation of these models is difficult and often overlooked or treated at a very cursory level. We believe validation efforts should not begin *after the model is developed*, but should be conducted throughout the development process, from beginning design to final product. A group of experts from both the using community and the model development community should be established to oversee and assist in the development effort. They can evaluate the model's structure, rules, and procedures to ensure they match real world functions and processes.

Validation efforts can also be enhanced by making models more transparent and easier to understand. Modern languages and structured programming techniques can help provide transparency; a well-conceived descriptive framework can provide thorough documentation of the model to foster understanding on the part of the user.

Validation efforts should continue throughout all phases of the development cycle. These efforts should take full advantage of whatever actual data are available, for example data from exercises, peacetime operations, or actual contingencies.[4] Test data sets should be developed that can be used as benchmarks for the new model as well as for existing models.

[4]We expect Operation Desert Shield will provide invaluable data for validating current and future mobility models.

Develop Richer Objective Functions and Cargo Assignment Rules

Development efforts should be directed at ways to enrich the objective function and assignment rules of a new model. A new model should not be driven just by transportation asset utilization or by just time-oriented measures, but by some combination of combat and budget measures. Because there are multiple attributes associated with deployment plans, methods should be explored to incorporate multiple objective functions or to use multi-attribute utility approaches. If the model's objective function is developed carefully, different degrees of importance, or weights, may be applied to the various criteria to reflect different problems or the different details of the mobility environment.

The rules used to schedule cargoes on transportation assets should have methods to look ahead and determine the implications of delaying the shipment of cargoes. These procedures should use some measures of priority to determine which cargoes to ship when transportation assets are scarce. Finally, the cargo assignment rules within the model should incorporate the interrelationships and linkages among forces, support, and resupply. The model must be "smart" enough to know that if a combat unit is delayed, its associated support and resupply may also be delayed.

In addition to logistic and efficiency-oriented measures, the new model should produce output measures that have more meaning to operational planners. Decisionmakers must be able to quickly understand the effect on operations of units arriving later than planned or of bottlenecks in portions of the overall system. Different techniques—ranging from combat-oriented measures or "scores" for units and weapon systems, to ties with combat simulation models—must be investigated to develop the operationally oriented measures.

Develop Methods for Increasing Robustness of Forces and Plans

Finally, the model development effort should explore techniques for increasing the robustness of the resulting mobility forces and plans. A "robust" solution to a requirements determination problem would be a mix of transport resources that can be expected to work well over a range of situations or contingencies. This can be contrasted with an "optimal" mix for a particular situation, which may be quite inferior if the world does not unfold precisely as specified for that situation.

The different sources and types of uncertainty must be identified, and their effects should be understood and captured in the new model. The solution methods employed by the model must develop plans that

work over a wide range of contingencies,[5] possibly developing confidence intervals as well as point estimates.

Two Technologies Should Be Explored

We believe two technologies offer promise for a new model. Because each approach has strong points and potential problems, we recommend that two parallel, but coordinated, prototype efforts be undertaken. One prototype should use mathematical programming techniques; the other should use knowledge-based modeling technology.

Mathematical Programming Technology. Mathematical programming techniques can directly estimate optimal mixes of resources for resource planning.[6] Such techniques also provide measures of sensitivity and of slack in the system, both of which are helpful in examining tradeoffs between and among forces.

Although mathematical programming models can represent most physical aspects of the mobility system, they sometimes have difficulty capturing the informal and personal decision processes that also are a part of the system. In addition, the overall size and complexity of the mobility system often results in models that can be formulated but that cannot be solved in reasonable times. To attain reasonable solution times, mathematical programming models of complex systems use simplifying assumptions, or they relax some constraints. The resulting model often no longer adequately represents the real system. In each case, the optimal solution to the "relaxed" model may not even be a feasible solution to the real-world problem being examined.

Current advances in hardware technology and algorithm developments may overcome some, or all, of these problems. For example, the Military Airlift Command is currently using a KORBX computer to solve large-scale linear programming problems. Parallel processing may also offer breakthroughs in considerably reducing solution times of large-scale problems.

Knowledge-Based Technology. An emerging technology we believe offers numerous benefits is knowledge-based modeling.[7] Knowledge-based models can represent both the physical aspects of the system and the informal decision logic and expert rules often used

[5]Deriving CINCs' preferences and understanding the robustness of a set of transportation assets may require both a transportation requirements model and a combat-oriented model. These two models, properly interfaced to facilitate the flow of data between them, may provide better insights into transportation force requirements than a single model or two models acting independently.

[6]Appendix C provides a more thorough description of the potential of mathematical programming technology.

[7]Appendix B provides a more thorough discussion of this technology.

during system operations. These models may also work in two directions, using forward chaining techniques to go from a starting condition to a final goal, and using backward chaining techniques to find a starting point that will yield a desired goal. This latter capability would be important for resource planning studies where questions involve the movement assets needed to attain a desired closure profile. Finally, knowledge-based models can be very transparent and easy to understand and modify.

Knowledge-based techniques, however, also are not without problems. The technology is still emerging, and there is no guarantee that solutions from backward chaining are "optimal" in any sense. Nevertheless, the technology is being applied in interesting ways.[8]

We recommend that both knowledge-based modeling and mathematical programming prototypes be developed to better understand the advantages and disadvantages of each. The eventual model may actually be a combination of the two techniques, a mathematical programming model of a "simplified" system generating initial optimal answers that are run through a knowledge-based model of the more complete and complex system to test feasibility of the solution, or a knowledge-based model that calls optimization routines for specific tasks. Feedback and iterations between the two models may ultimately provide "answers" to mobility questions.

The development of any new model, especially one that is radically different from existing models, is a formidable undertaking that does not guarantee success.[9] However, given the importance of requirements determination studies for the JS/J-4, especially in the current climate of changing world politics and defense budgets and the shortcomings of current models in this area, a new model designed specifically for requirements studies is sorely needed. Such a model would greatly benefit the mobility analysis surrounding force structure and budget issues, and attributes of that model would benefit the deliberate and crisis action planning arenas as well.

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[8]See John F. Schank and Brian Leverich, *Decision Support for the Wartime Theater Ammunition Distribution System: Research Accomplishments and Future Directions*, RAND, R-3794-A, June 1990, for a description of a knowledge-based that models the distribution of ammunition in a wartime theater of operations.

[9]At the conclusion of the research described in this document, the JS/J-4 asked RAND to formulate a functional description of the new model and to begin developing prototypes using mathematical programming and knowledge-based techniques.

Appendix A

DETAILED DESCRIPTION OF CURRENT MODELS

This appendix gives detailed descriptions of MIDAS, RAPIDSIM, and TFE. MIDAS is the major example, and the other models are generally described only in the ways they differ from MIDAS.

MIDAS

MIDAS (Model for Intertheater Deployment by Air and Sea) is the primary strategic mobility model used by OSD (PA&E) and SCAD, and is used solely for resources planning.[1] A fairly high-level model, MIDAS uses heuristics to schedule cargo in a timely manner without gross inefficiency in the use of transportation resources. However, MIDAS is written in PL/1, an outdated computer language that has poor programming support on the Honeywell 6180 mainframe.

Data Preparation

The first step in running MIDAS is acquiring the appropriate input data, a complicated procedure that can take weeks or months, depending on the study. Data may be gathered from several different sources, such as OSD or the services, and then it must be cleaned and massaged into the appropriate input format for MIDAS. Data preparation is generally the lengthiest and costliest step in modeling.

MIDAS uses three input files: a requirements file, a ships file, and a scenario file, which also contains airlift information. Depending on the study, data entered into these files may have come from the JOPS system or the services, or may be wholly hypothetical. The MIDAS input files are generally at a much higher level of aggregation than files provided by JOPS or by the services; for example, in MIDAS the entire CONUS may be modeled as having only West Coast, East Coast, and

[1]Several versions of MIDAS currently exist, and more are under development. In addition to the Honeywell version used by the Joint Staff, MIDAS has been ported to the IBM 3090 by GRC and the VAX by JDSSC. GRC has developed a PC version called MINOTAUR, and MRJ has studied the feasibility of porting MIDAS to the Connection Machine, a computer that uses massive parallel processing to speed execution. A version featuring multiporting is used by OSD (PA&E) for studying POL movement.

Gulf ports, whereas data from JOPS or the services may refer to 50 or more ports.[2]

Prioritize Records

MIDAS determines cargo priority based on deadlines provided by the CINCs and the services. MIDAS sorts the cargo requirements file primarily by the CINC's RDD less estimated travel time, and secondarily by the Ready to Load Date (RLD). The sorting is a strict ranking; i.e., no allowance is made for tradeoffs in priorities. This strictness caused problems in the RIMS study.[3]

Mode Selection

The next step is mode selection. During scheduling, MIDAS compares load/transit/unload times by air and sea, and if not prespecified by the services selects the mode that will result in the earliest delivery of the unit. Because MIDAS considers load/transit/unload times in prioritizing cargoes, it carries "open-moded" cargoes on both air and sea lists. Then on the earliest day the movement record is scheduled, it reevaluates all those cargoes with updated estimates of travel and loading times. (This mode selection feature was not used in RIMS.)[4]

Air Cargo Scheduling

For each movement record, MIDAS identifies the major cargo type (e.g., passenger, bulk, oversized, outsized). It identifies the aircraft that has the highest priority for that type of cargo, then computes aircraft operating hours required to move that cargo, then sees if the preferred aircraft type has enough operating hours available. If it does, the movement is scheduled; if not, the next-preferred type of aircraft is checked for availability.

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[2]The analyst can, if desired, model up to 39 total SPOEs and SPODs. Expanding the number of ports increases model runtime.

[3]MIDAS loads and dispatches mobility assets as rapidly as they and compatible cargo become available rather than assigning these assets to cargoes in a way that would more closely achieve the specified deployment schedule. As a result, the model may use a fast ship to deliver early cargo that is available rather than reserving that ship to deliver cargo available later in a more timely manner. Therefore, a late delivery may not always be caused by lack of the right amount or type of shipping but by the limitations of the model.

[4]The RIMS analysts determined that the mode selection algorithm internal to MIDAS was inappropriate for satisfying the study objectives. As a result, an alternative decision logic was used in a preprocessor to the MIDAS model to allocate movement requirements with no specified mode to either airlift or sealift.

Sea Cargo Scheduling

MIDAS searches for the ship that will deliver the cargo the earliest, considering time for ferry, loading, travel, and unloading. The model searches for partially loaded ships first, then for recently used ships (which are not considered available until fully unloaded), then for ships not yet used. This can result in an apparent contradiction: cargo shortfalls *and* unused ships. But some ships do not get used because they are too slow or are not the right "type" of ship. Nevertheless, during the RIMS study there were complaints that this scheduling technique was not realistic.[5]

One important characteristic of the MIDAS sealift scheduling algorithm is that MIDAS first checks for the availability of ships previously used in the simulation run before checking for ships not previously used. This may result in ships not being used, as was noted in RIMS.

Air Movements Simulation

In simulating airlift, MIDAS uses load factors and utilization factors instead of simulating individual aircraft. Airlift activities are represented by daily productivity calculations:

(1) Cargo Moved = Sorties Flown × Aircraft Payload ("×" indicates multiplication)
(2) Sorties Flown = Flying Hours × Speed/(2 × Distance)
(3) Flying Hours = Number of Aircraft × Utilization Rate

"Utilization Rate" is an hours per day figure giving an estimate of the average productive number of flying hours per aircraft. "Aircraft Payload" figures reflect availability of space for passengers, bulk cargo, "oversize" cargo, and "outsize" cargo.

Sea Movements Simulation

Although MIDAS does not simulate individual airlift, it does simulate individual ship movements and even identifies ships by name.[6] POE berthing and loading are simulated, and then ships are tracked

[5]Given that the primary measure of effectiveness of the MIDAS model is to minimize overall lateness over the entire set of movement requirements, the model schedules cargo to be moved on the "best" ship available. Accordingly, the model will consistently choose only the most accessible, the fastest, and the most easily loaded ships, even though in reality all ships, regardless of their shortcomings, would be used.

[6]MIDAS can consider the effect of convoying and attrition, although in practice these features seem to be rarely used. It also allows automatic calculation and scheduling of force resupply.

from their POE to convoy assembly point (if the optional convoying feature is used) and on to the POD, where POD berthing and unloading are simulated.

There is no provision in MIDAS for changing the route of a ship in mid-sail if the POD is destroyed. Instead, it is generally assumed that because many ports are aggregated into a POD centroid, the ship would simply sail to the closest open port in the centroid. However, if all the ports in a centroid are destroyed, then a ship will sail to its POD and remain stuck there waiting to unload.

Prepare Reports

MIDAS produces tabular reports and databases, which are voluminous. The printed reports show how well movement requirements are met and also show which transportation resources were utilized and how many. The first database gives the detailed movement schedule of each requirement, the second summarizes utilization of airlift and sealift, and the third provides data on the efficiency of ship loading for each ship. Production of the second and third databases is optional.

RAPIDSIM

RAPIDSIM (Rapid Intertheater Deployment Simulation Model), the direct ancestor of MIDAS, is very similar to MIDAS and uses similar heuristics to schedule cargo. There are two major differences:[7] (1) RAPIDSIM does not prioritize cargo records internally, and (2) it spans a smaller distance of the transportation network (it does not cover movement from origin to POE, or from POD to destination). This model requires extremely sophisticated users. Only experts can prepare the database, run the model, and interpret output.

Data Preparation

The initial data preparation steps are similar to those associated with MIDAS. Similar input files are gathered, and records are aggregated to much the same level. The movement requirements file is derived from the MORSA file. Cargo records must be sorted in order of priority by the analyst.

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[7]Another feature of RAPIDSIM is that it can be used to track cargoes day by day. This feature has been used in some exercises at the Naval War College.

Mode Selection

RAPIDSIM selects the mode for each piece of cargo based on (1) the preferred transportation mode for each cargo, (2) the availability of transport, and (3) the delivery times of the different modes.

Scheduling and Movement

Like MIDAS, RAPIDSIM uses discrete simulation to model sealift and uses flow calculations to simulate airlift. Cargo capacity is measured solely in short tons instead of considering cargo volume as well. This can lead to such problems as "loading" 15 helicopters into a single C5-A.

Prepare Reports and Graphics

RAPIDSIM produces voluminous tabular reports on cargo delivery and transportation asset usage and can produce a plethora of detailed and informative graphics.

TFE

TFE (Transportation Feasibility Estimator) is used to establish the gross transport feasibility of a CINC's TPFDD through simulating cargo movements.

Data Preparation

The analyst provides the OPLAN-specific TPFDD movement requirements file and ship availability file, while the rest of the files come from JOPS: numbers and type of transportation assets (ASSETS), geographic locations (GEOFILE), characteristics of airlift and sealift resources (CHSTR), characteristics of ports (APORTS, PORTS), movement characteristics of standard units (TUCHA), and standard distances (SDP). The TPFDD specifies the transportation mode for each piece of cargo.

Scheduling and Movement

TFE simulates airlift and sealift in a similar manner to MIDAS and RAPIDSIM but can handle many more movement requirements, airports, seaports, and transportation assets than either of the other two models. For example, while a typical MIDAS run may deal with just

6,000 movement requirements, TFE will generally handle 80,000 requirements. TFE is the most detailed model currently in use.

Prepare Reports

TFE can produce 31 different reports on requirements, airlift assets, and sealift assets.

Appendix B

KNOWLEDGE-BASED MODELING TECHNOLOGY FOR STRATEGIC MOBILITY

Existing strategic mobility models often employ idiosyncratic modeling methods, characterized by ad hoc structures that tend to confuse implementation concerns with modeling concerns. For example, a model may represent cargo types by an array that shows preferred transport modes and priorities for each type, without making clear whether this representation is chosen because it is believed to be the most appropriate way of *modeling* cargo types or simply because it is the most convenient way to *implement* them in the chosen programming language. Such decisions have a direct and profound effect on the comprehensibility of a model: The more they are based on modeling concerns, the more comprehensible the resulting model will be. This is a crucial factor in making models more easily validated and more credible. A first step toward improving the credibility of a model is therefore to improve its comprehensibility by separating its modeling concerns from its implementation concerns. That is, it should be made clear whether each decision in the design of a model is motivated by the desire to represent the real world appropriately or by the constraints of the available programming language and environment. Motivating a model's design decisions in this way makes it much easier for domain experts and users to see which aspects of reality the model represents, how it represents them, and how it arrives at its results.

Traditional software modeling efforts use a restricted set of concepts that are not always powerful or flexible enough to represent reality in comprehensible ways. Aside from scheduling and queuing facilities and some support for probability distributions, most traditional modeling environments provide little more than bare programming languages, which tend to provide few modern programming constructs to facilitate comprehensible representation. However, recent advances in modeling languages and methodology are producing new approaches that appear to be directly applicable to strategic mobility modeling.

OBJECT-ORIENTED SIMULATION

There is a growing trend in the military modeling community toward object-oriented modeling, which focuses on the real-world objects of

interest for a given modeling effort (for example, ports, ships, units for mobility modeling). Each such object—or *class* (collection) of objects—is represented in the model by a separate construct called an *object*. For example, a mobility model might contain *objects* representing ports, ships, units, etc. Each *object* in the model is described by "attributes" and "behaviors." The attributes of an *object* describe various aspects of the object; for example, a ship *object* might have attributes describing its speed and capacity. The behaviors of an *object* (sometimes called its "methods") describe the actions it can perform; for example, a ship *object* might have behaviors for loading, unloading, and sailing to a given destination. All activity in an object-oriented model is represented by *objects* asking each other to perform appropriate behaviors; such requests are called *messages*. Since *objects* in the model may represent classes of real-world objects, a given type of cargo might be represented by an *object* having attributes that describe the preferred transport modes and priorities for that type of cargo. Similarly, each type of ship or aircraft might be represented by a separate *object*. Particular ships or aircraft would be represented as *objects* that are "instances" of their respective classes.

One of the major advantages of the object-oriented approach is its ability to represent classes of objects, which can be used to define "class-subclass hierarchies" that allow most entities in the model to be described as variants or specializati[illegible] [illegible]her entities; this introduces valuable structure into the model and allows it to represent similarities among entities in the real world. For example, all transport vehicles might be represented by a Vehicles class having attributes for capacity, speed, mode-of-travel, etc. (without specifying values for these attributes) and having default behaviors for loading and unloading. Cargo ships might then be represented as a subclass of Vehicles called Ships (using plural names for classes, such as "Ships," emphasizes the fact that a class represents the collection of all such objects). The class Ships automatically "inherits" all the attributes and behaviors of its parent class, Vehicles; however, it can supply its own values for these inherited features, and it can add others of its own. For example, Ships might supply the value "sea" for the mode-of-travel attribute it inherits from Vehicles, while still having no values for capacity and speed; similarly, Ships might supply specialized behaviors for loading and unloading and might add its own unique behavior for sailing from one port to another. A particular type of cargo ship might be a CargoA subtype of Ship, with appropriate values for capacity and speed. The model might generate several instances of CargoA ships, named CargoA1, CargoA2, etc. Similar hierarchies could be defined for aircraft, ports, cargo types, units, etc. Defining appropriate *objects* in this way is an example of "object-oriented data modeling," which is one of

several related approaches that go beyond current relational data modeling.

This use of class-subclass hierarchies and inheritance produces models that are easier to grasp and to modify. In the above example, all information about ships in general is contained in the single *object* Ships; any information about a particular kind of ship is contained in the appropriate subclass definition for that kind of ship, and any information that applies equally to ships and aircraft is contained in the parent class Vehicles. This makes a model easy to understand, because all information about an object is either represented within the object itself or is apparent from the classes to which it belongs. Similarly, inheritance minimizes the redundant description of similar or identical entities: Changing a model is therefore far less likely to produce the kinds of inconsistencies that plague most other modeling approaches.

Proponents of object-oriented modeling are sometimes overzealous in their claims. While the approach has the advantages illustrated above, it also has several shortcomings (Rothenberg, 1986). In particular, it does not do much to improve the comprehensibility of complex behavior involving multiple or composite objects. For example, the structure described above might reveal the behavior of the model in terms of transport vehicles, but it would be unlikely to provide much insight into the behavior of units that are broken up to be shipped by multiple vehicles because the object-oriented approach lacks aggregation constructs (which makes it difficult to define a unit as a single *object* consisting of multiple components, each of which can be shipped separately) and is unable to define behaviors that involve multiple objects (which makes it difficult to view the arrival of all of a unit's components as a single event).

More fundamentally, object-oriented models retain the limitations of traditional modeling approaches that merely specify the initial states of a simulated world and then run the simulation to see what happens. This "toy duck" view of simulation ("wind it up and see where it goes") corresponds to asking questions of the form "What if . . . ?" ("What would happen if a system having the given behavior were to proceed from the given initial state?"). Yet there are many other kinds of questions that are of at least as much importance in many situations (Davis, 1982; Ericson, 1985; Rothenberg, 1986). These include such questions as:

- Why did Ship X wait until Day 4 to depart?
- Under what conditions will Unit X arrive at its port of debarkation by Day 3?

- How can aircraft of type X best be utilized?
- What is the earliest that Unit X can arrive at its destination?
- What is the best mix of lift assets to achieve a given closure profile?

Such questions go beyond "What if . . . ?" (Rothenberg, 1988) and are extremely difficult to answer using traditional or object-oriented modeling technology. Simulation is often used to search for such answers (sometimes referred to as "sim-optimization," when an optimal answer is sought) by running the simulation many times, in the hope that the desired answer will result from one of these runs. However, this is very inefficient and can never guarantee that the search will converge toward the desired solution. New knowledge-based modeling concepts (such as those described below) should allow questions like these to be answered using artificial intelligence (AI) techniques that perform inferences going beyond mere simulation.

KNOWLEDGE-BASED MODELING

To go beyond these limitations, current modeling research has focused on a "knowledge-based" approach drawn from Artificial Intelligence. The term *knowledge-based* means that models explicitly show the knowledge on which they are founded; in this context, "knowledge" can be operationally defined as symbolic information in a form that is understandable and meaningful to a human expert while being interpretable by a computer. Information is "interpretable" by a computer if programs can be written to draw inferences from it (to make explicit what is implicit in the information). For example, knowledge about debarkation ports might state that they are only operational when they are served by rail lines, whereas knowledge about rail lines might state that they are only operational when they have not been disrupted by a rail strike. A human expert can understand, verify, or modify this knowledge, while a computer program can infer from it that a debarkation port will not be operational if there is a rail strike. (Expert systems are a subset of this knowledge-based approach that typically use "if-then" rules to attempt to replicate the behavior of a human expert in some limited domain.)

Knowledge-based modeling retains the key advantages of object-oriented modeling (such as the clarity and minimization of redundancy that result from class-subclass hierarchies with inheritance), but it provides a fundamentally broader view of modeling that has great potential for strategic mobility. This potential stems in part from the use of a "declarative" style of modeling, in which a model *declares what it*

does rather than *describing how to do it.* This allows a knowledge-based model to be analyzed in the abstract to answer questions beyond "*What if . . . ?*" in addition to performing traditional simulation to answer "*What if . . . ?*" questions. For example, a knowledge-based model can be made to explain why or under what conditions certain events occur or how a desired goal might be achieved. This potential for "goal-oriented" modeling appears to be directly applicable to answering resource requirements questions in strategic mobility.

Knowledge-based modeling also provides ways of representing complex relationships among entities, such as the relative priorities of transporting certain combinations of units by certain dates or the fact that certain key components of a unit constitute its core. The model builder can state these relationships in a straightforward, declarative manner (e.g., that components A, B, and C constitute the core of unit X) that is understandable to and therefore verifiable by a domain expert. At the same time, a computer program can draw automated inferences from these relationships, such as that a given collection of priorities may be impossible to satisfy. Knowledge-based approaches to representing complex relationships should permit the construction of models in which such relationships are much easier for modelers to see, understand, verify, and modify and can be interpreted automatically in useful ways. For example, this should facilitate capturing the CINC's priorities and preferences by using symbolic representations such as temporal logic rather than simple time windows to better reflect trade-offs and interdependencies among delivery dates.

An example of how the knowledge-based approach may apply to strategic mobility modeling can be found in work on a new declarative modeling formalism called DMOD, being developed under the RAND Advanced Simulation Language project (RASL) (Rothenberg et al., 1989). This formalism defines simulation models in terms of their *causality*, by specifying which events cause which other events under what conditions. Rather than computing and storing the state (attribute values) of the simulated world at each moment of simulated time as is done by most modeling approaches, DMOD computes and stores the "history" of events that have occurred during a simulation; values of attributes can be computed at any desired point in time by tracing their changes through this history. The model consists of a set of *causality rules*, specifying which events cause which other events under what conditions, and a set of *state-computation rules*, specifying how to compute the value of each desired attribute from the history.

This approach has several advantages. First, it makes it possible to validate models in a direct, interactive way. A DMOD model is stated in terms of *causes* rather than *actions*. A simulation using this model

shows the behavior of the modeled system in terms of causation rather than activity: The user sees causal relationships and their effects directly, rather than having to infer them from the behavior of the model. Instead of merely showing a confusing sequence of actions, the simulation shows which events cause which subsequent events. This produces a direct correspondence between the observed behavior of the model and the causal behavior of the system being modeled. The user need not *verify* that the simulation program correctly implements its model, since the correct interpretation of the declarative rules that constitute the model is guaranteed by the use of the DMOD formalism. Instead, the user can directly and interactively *validate* the model with respect to the real world: Any anomalous causes or effects in the behavior of the simulation express themselves as anomalies of the model itself. Instead of having to ask "Why did the program do *that*?" the user is able to ask "Is that the *actual* cause and effect in the real world?" Though there are other formalisms in which the readability of a simulation program helps the model builder ensure that the model is reasonable, DMOD adds to this the ability to witness the underlying validity of the model as a simulation unfolds.

The DMOD approach also allows one to analyze models with or without running them as simulations. This goes beyond "*What if . . . ?*" to answer questions about logical relationships in a model or definitive questions such as whether an event will ever occur or what the maximum value of a parameter can ever be. DMOD can answer such questions by performing inferences on the model itself, evaluating or proving assertions that will be true of the model in *any* simulation. Many questions can be asked of a DMOD model either *concretely* ("Was this true during a particular simulation run?") or *abstractly* ("Is it true of the model in general, for all possible simulation runs?"). Current research is exploring "goal-oriented" modeling in DMOD, which would allow requirements questions to be answered without the need to run a simulation many times in an effort to search for the desired solution.

DMOD retains the key advantages of object-oriented modeling, allowing the model builder or user to view the model in terms of objects and their relationships, but this *object view* is supplemented by an *event view* that emphasizes events and causality. Additional views can be defined, allowing a model to be built or analyzed in whatever way is most appropriate. For example, a strategic mobility model might be designed in terms of objects such as ports, cargo, and transport vehicles, but it might subsequently be analyzed in terms of events such as loading, embarking, sailing, unloading, and debarking. The final results of running a simulation under any of these views would be

the same (the "toy duck" would wind up in the same place), giving the same answers to "*What if . . . ?*" questions. However, each view would allow answering different kinds of questions. For example, the *object view* would allow answering such questions as "How many ships were waiting to be loaded at Port X on Day 3?" or "Which unit arrival dates depend directly or indirectly on the maximum speed of CargoA ships?" while the *event view* would allow answering such questions as "What events caused the bottleneck at Port X on Day 3?" or "What events may be directly or indirectly caused by the arrival of a CargoA ship?"

CONCLUSION

The credibility and utility of strategic mobility models can be improved by the use of advanced modeling technology. Representation techniques based on object-oriented data modeling and simulation should make mobility models more comprehensible and more easily modifiable. Declarative modeling techniques should make mobility models more amenable to validation and therefore more credible. Knowledge-based inferencing techniques should allow mobility models to answer questions beyond "*What if . . . ?*", improving their utility in situations that currently require large numbers of runs to search for answers. Current research efforts such as the DMOD formalism appear to hold great promise for strategic mobility modeling.

Appendix C

MATHEMATICAL PROGRAMMING TECHNOLOGY FOR STRATEGIC MOBILITY

INTRODUCTION

The approaches to military mobility modeling described in this appendix utilize the techniques of mathematical programming. Problems of optimization—maximizing or minimizing some weighted sum of decision variables subject to the constraints of loading, unloading, and carrying capacities; limited numbers of lift assets, manpower, and materiel availability; and required closure profiles—are easily stated as pure or mixed integer programming problems. Their analytical solution, however, may or may not be currently attainable, depending upon the size of the problem and the computational complexity of the solution algorithm. Most of the decision support systems currently in use for related problems in nonmilitary areas such as vehicle routing and scheduling for trucking companies, shipping companies, and airlines utilize heuristics, either by themselves or in conjunction with analytical solution techniques (see Brown et al., 1987, for example, as well as Abara, 1989, and Gershoff, 1989, which will be discussed below). While these heuristics usually result in "acceptable" operational policies—and, in general, these decision support systems are used for deliberate and crisis action planning rather than long-term resource planning—they do not necessarily result in optimal solutions. Even when the accuracy of the heuristics can be demonstrated, their use in resource planning is severely limited by their inability to perform the kinds of sensitivity analyses that exact mathematical programming algorithms routinely provide.

The only meaningful rationale for the use of heuristics over analytically obtained, optimum solutions is the computational problem mentioned earlier: It may not be possible to obtain the solution to the mathematical programming problem in the real-time operational environment. Even here, the mathematical programming solutions are needed to validate the proposed heuristic set of decision rules. A realistic sample of operational situations would have to be presented to the heuristics and the generated solutions compared with those obtained

from the programming model to assess their "closeness" to the optimum solutions. Substantial deviations from optimality could demonstrate weaknesses in the heuristics and highlight where improvements are needed.

The importance of sensitivity analysis cannot be overemphasized. In mobility modeling, such factors as the closure profile and the earliest availability of units are usually specified as "givens." The sensitivity analyses of mathematical programming parameters, which are routinely obtained as part of the solution to the problem, can be used to investigate the "costs" of these givens: How much of a savings (in dollars, in time, in numbers of lift assets) could be achieved by relaxing some of these specified values? What units could delay their availability without adversely affecting either the closure profile or the number of required assets? What would be the effect on the objective function if certain units were in a higher state of readiness and available a day earlier? What would be the effect if certain materiel could arrive at the POD a day later? In addition to providing a basis for resource planning, these analyses can provide inputs to CINCs and their staffs to assist them in readiness, mobilization, and contingency planning.

As the preceding discussion illustrates, resource planning can have more than one measurable goal. Heuristics are usually derived with only a single goal in mind. *Goal programming* is a generic term applied to mathematical programming techniques that are oriented toward achieving several goals. These techniques involve mathematical programming with objective functions that reflect the multiplicity of desired attributes. One common technique is *preemptive goal programming*, in which goals are prioritized and goal achievement is maximized subject to the requirement that no higher priority goal is adversely affected. Other approaches to goal programming involve expressing the objective function as a weighted sum of the various goals. *In multiattribute utility theory* (MAUT) the weights represent additive utilities, whereas in the *analytic hierarchy process* (AHP) method they represent multiplicative utilities. For a discussion of the pros and cons of these approaches, see Winkler, 1990, and the papers that follow it.

One class of mathematical programming models that provides exact answers and has, in fact, been incorporated in some CONUS mobility models is the *transportation algorithm*. The major difficulty with this approach is its inability to model sealift problems where multiporting is an option. The transportation algorithm is used as a component of SAIL (Scheduling Algorithm for Improving Lift), a part of MSC's SEASTRAT system, but the "optimum" results provided by the transportation algorithm are infeasible for multiport sealift capability. It provides a starting point for the heuristics, which attempt to find a

feasible solution that retains as much of the optimum solution as possible.

The multiport nature of sealift can be modeled using the formulation, "dial-a-ride," particularly the *multivehicle, many-to-many dial-a-ride problem with time windows.* As alluded to earlier, the major difficulty in utilizing this model is computational.

TRANSPORTATION MODELS

The transportation algorithm of linear programming solves the following problem: Several sources each have a stated supply of some commodity and several destinations each have a stated demand for that commodity. The cost of shipping one unit of the commodity from source i to destination j is known. What is the least cost way to meet the demands from the supplies? If the amounts that can be shipped from some or all of the sources to some or all of the specified destinations are limited by shipping capacity constraints, the problem is called a *capacitated* transportation problem.

The SCOPE transportation model was developed by Jarvis and Ratliff, 1983, for the Joint Deployment Agency under a contract with the Office of Naval Research. It utilizes the transportation algorithm to allocate lift assets to routes (here called "channels") and schedule the movement of materiel to meet time window requirements at the destinations, subject to the constraints imposed by the loading capacities at the POEs, the unloading capacities at the PODs, the available lift assets, and the initial location of the materiel. It can be applied to airlift and sealift as long as each lift asset has only a single POE and single POD; it cannot handle multiport tours.

In the LIFTCAP submodel of SCOPE, the origins are taken to be the POEs, and destinations are the PODs. The "supply" at a POE is its loading capacity and the "demand" at a POD is its unloading capacity. The unit "cost" is the time required for a lift asset to load at the source, travel to the destination, unload, and return to the source to be ready to run again. The solution to this problem maximizes the total amount that can be moved per unit time and, hence, determines the number and deployment of lift assets needed to achieve this maximum throughput. If the number of assets that can use a given POE-POD channel is limited (for example, by minimum headway requirements), then the model is run as a capacitated problem.

LIFTCAP requires all lift assets to be identical. If there are, for example, three types, the number of sources and destinations is tripled, with "shipments" from a source corresponding to one type of asset to a destination corresponding to a different type prohibited.

Another use of LIFTCAP is to maximize the throughput for a *given* limited set of lift assets—how should these assets be apportioned among the POE-POD channels to maximize throughput?

The MRMATE submodel of SCOPE schedules specific materiel on the lift assets. In this formulation, each movement requirement is a "source" and its "supply" is the amount to be moved. The "destinations" are all combinations of POE, POD, and day of operation; if there are n POEs, m PODs and p days of operation, there are nmp destinations. The demand at a destination is the capacity of that POE-POD channel on that day, determined by the number of lift assets assigned, perhaps by LIFTCAP. Shipments that violate time window constraints on either end are prohibited. If all nonprohibited shipment unit costs are set equal to zero, a feasible solution to the problem demonstrates that the required closure profile can be met with the assigned lift assets. The model can also minimize the sum of deviations from desired delivery times or to maximize the rate of supply. If no feasible solution can be found, MRMATE can be used to find the delivery schedule that minimizes the number of ton-days of lateness.

MULTIVEHICLE, MANY-TO-MANY "DIAL-A-RIDE" PROBLEM WITH TIME WINDOWS

Describing the strategic mobility scheduling of cargo and manpower movement requirements in terms of the "dial-a-ride" problem can be accomplished in the context of the Solomon and Desrosiers, 1988, formulation. The objective function is quite general and can be made to reflect some or all of the following costs: number of lift assets used, number of "tons-late," number of miles covered, and completion time, as well as including any special costs involved with choosing specific legs on a lift asset's tour. As in the transportation type model, all lift assets are assumed to be identical; however, whether the problem can be decomposed into subproblems for each class of asset is not yet clear.

Each movement requirement becomes two nodes in the network: one at which it is picked up, the second at which it is delivered. Initially, all vehicles are assumed to be available in a "depot," and vehicle tours are generated as a series of "arcs," each representing a movement from one node to another. A certain amount of preprocessing is done to eliminate arcs that are not feasible. Two examples:

- If picking up cargo at u at its earliest availability and making the next stop at w would prevent the cargo from reaching its destination before its latest allowable delivery time.

- If cargo is loaded at successive nodes, the combined cargo at those nodes exceeds the capacity of the lift asset.

The problem constraints state that the first stop of each lift asset must be at a POE, the last must be a POD, every movement is picked up, every movement is delivered, the asset that makes the pickup is the same as the asset that makes the delivery at a later time, the capacity of the vehicle is never exceeded, and all nodes are visited within their time windows. Other constraints are merely definitions—for example, if an asset travels from node u to node w, its arrival at w is the arrival time at u plus the time spent at u plus the travel time from u to w.

A detailed mathematical formulation of the problem is presented in the following sub-section for those interested in these details. Those interested in a broader view of the problem might want to skip the discussion of *Mathematical Formulation* and proceed directly to *Other Considerations.*

Mathematical Formulation

Suppose that there are n movement requirements. Requirement i will be picked up at a POE labeled node i and delivered to a POD labeled node n + i. Nodes 0 and 2n + 1 represent the common depot from which the lift assets are drawn and to which they return. Clearly, different nodes will correspond to the same physical location; some subsets of nodes will refer to the same POE or POD. Define

N = $\{0,1,2,\ldots,2n,2n+1\}$, the set of nodes
P_+ = $\{1,2,\ldots,n\}$, the set of pickup nodes (POEs)
P_- = $\{n+1, n+2,\ldots,2n\}$, the set of delivery nodes (PODs)
P = $P_+ \cup P_-$, the set of nodes other than the depot
d_i = size of movement i, shipped from $i \epsilon P_+$ to $(n+i) \epsilon P_-$
$[a_i,b_i]$ = pickup time window at POE for movement $i \epsilon P_+$
$[a_{n+i},b_{n+i}]$ = delivery time window at POD for movement $i \epsilon P_+$
V = number of identical lift assets
D = capacity of each lift asset. This could be a vector if more than one measure of capacity is pertinent.
$[a_0,b_0]$ = time window for lift assets leaving the depot
$[a_{2n+1},b_{2n+1}]$ = time window for lift assets returning to depot
t_{uw} = travel time (possibly zero) from node $u \epsilon N$ to $w \epsilon N$
c_{uw} = travel cost from node $u \epsilon N$ to $w \epsilon N$

s_u = service time (pickup time or delivery time) at node $u \epsilon N$

with $s_0 = s_{2n+1} = 0$

K = fixed cost incurred if a lift asset is used.

Note that the time horizon or duration of this set of movements is $b_{2n+1} - a_0$.

If the movement requirements can be labeled such that for all $1 \leq i \leq k \leq j \leq n$ the inequalities $t_{ij} \geq t_{ik}$, $t_{ij} \geq t_{kj}$ and $t_{ij} \leq t_{ik} + t_{kj}$ all hold, the problem is called the *shoreline* problem. Here, the movement requirements have been labeled such that all movements from the same POE are numbered contiguously beginning with the POE nearest (in time) to the depot. After completing the numbering of movements at a POE, the labeling continues at the nearest POE to the one just completed, whose movements have not yet been numbered. This aggregates movements at POEs as if the POEs were points along a shoreline. It is not always possible to do this on a land mass where aircraft are used as lift assets. For example, if there are three POEs located at coordinates (3,0), (4,10) and (30,0) with respect to the depot at (0,0), they would be nodes 1, 2 and 3, assuming only a single movement from each. If each leg has the same constant velocity then the travel times are proportional to the distances; t_{12} is proportional to 10.05, t_{13} is proportional to 27 and t_{23}, is proportional to 27.86. Thus, $t_{12} < t_{13} < t_{23}$, which violates the condition.

If the dial-a-ride problem is restated eliminating node 2n + 1 (the return to the depot), the resulting problem is referred to in the literature as the *pickup and delivery problem with time windows*. The algorithms for this problem are usually the same as for the dial-a-ride problem.

The arc (u,w) [$u,w \epsilon N$] is retained in the network if and only if, first,

$a_u + s_u + t_{uw} \leq b_w$ (that is, the earliest beginning of service at u plus the time required to perform the service and travel to w would get the asset to w before its latest allowable time there)

AND for distinct u and w

$d_u + d_w \leq D$ if $u,w \epsilon P_+$ OR if $u,w \epsilon P_-$ (there is sufficient capacity in the lift asset to make successive pickups of movements u and w or deliveries of movements u − n and w − n).

The decision variables are

$X_{uw}(v)$ = 1 if lift asset v travels from node $u \epsilon N$ to node $w \epsilon N$
= 0 otherwise,

Y_u = total load being carried by a lift asset after its stop at $u \epsilon P$. This could be a vector if more than one unit of capacity is pertinent.

T_u = time of start of service at node $u \epsilon P$,

and for all $v = 1,2, \ldots ,V$

$T_0(v)$ = time lift asset v leaves the depot

$T_{2n+1}(v)$ = time lift asset v returns to depot.

The constraints on the problem in addition to the definition of $X_{uw}(v)$ as a zero-one variable are

$$\sum_{w=1}^{n} X_{0,w+n}(v) = 0 \text{ for } v = 1,2, \ldots , V;$$

for each lift asset, the first stop after leaving the depot cannot be at a POD.

$$\sum_{w=0}^{2n+1} X_{uw}(v) - \sum_{w=0}^{2n+i} X_{wu}(v) = 0 \text{ for } u \epsilon P, v = 1,2, \ldots , V;$$

for each lift asset and each node other than the depot, the number of entries into that node from any other node by that asset – or 1 – must equal the number of exits from that node to some other node by that asset.

$$\sum_{v=1}^{V} \sum_{w=0}^{2n+1} X_{uw}(v) = 1 \text{ for } u \epsilon P;$$

each node other than the depot is entered exactly once from some other node by some lift asset. Note that this precludes the possibility of a movement being shared by more than one lift asset.

$$\sum_{u=1}^{n} X_{u,2n+1}(v) = 0 \text{ for } v = 1,2, \ldots , V;$$

for each lift asset, the last stop before returning to the depot cannot be at a POE.

$$\sum_{w=0}^{2n+1} X_{uw}(v) - \sum_{w=0}^{2n+1} X_{w,n+u}(v) = 0 \text{ for } u \epsilon P_+, v = 1,2, \ldots , V;$$

the same lift asset that makes a pickup at node u makes a delivery at node n + u.

$$T_{n+u} - T_u \geq s_u + t_{u,n+u} \text{ for } u \epsilon P_+;$$

the pickup at node u must precede the delivery at node n + u, that is,

$$T_{n+u} \geq T_u + s_u + t_{u,n+u}.$$

$$Y_0 = 0;$$

all departures from the depot are empty and

$$0 \leq Y_u \leq D \text{ for } u \epsilon P_+;$$

following each pickup, the lift asset is not loaded beyond capacity.

$$T_w - T_0(v) - b_{2n+1}X_{0w}(v) \geq t_{0w} - b_{2n+1} \text{ for } w \epsilon P_+, v = 1,2, \ldots, V;$$

if lift asset v makes its first stop at node w, the arrival at w cannot be earlier than the time asset v leaves the depot plus the travel time from the depot to node w. If $X_{0w}(v) = 0$ then vehicle v does not make its first stop at w and the constraint is nonbinding since LHS > 0 > RHS.

$$T_w - T_u - b_{2n+1}X_{uw}(v) \geq s_u + t_{uw} - b_{2n+1} \text{ for } u,w \epsilon P, v = 1,2, \ldots, V;$$

for every lift asset and every arc in the network: if asset v travels from node u to node w the arrival at w cannot be earlier than the arrival time at u plus the service time at u plus the travel time from u to w. If $X_{uw}(v) = 0$, constraint is nonbinding, as above.

$$T_{2n+1}(v) - T_u - b_{2n+1}X_{u,2n+1}(v) \geq s_u + t_{u,2n+1} - b_{2n+1}$$
$$\text{for } u \epsilon P_-, v = 1,2, \ldots, V;$$

if lift asset v makes its last stop at node u its arrival at the depot cannot be earlier than the arrival time at u plus the service time at u plus the travel time from node u to the depot. If $X_{u,2n+1}(v) = 0$, the constraint is nonbinding, as above.

$$DX_{0w}(v) - Y_w \leq D - d_w,$$

$$DX_{0w}(v) + Y_w \leq D + d_w \text{ for } w \epsilon P_+, v = 1,2, \ldots, V;$$

if lift asset v makes its first stop at w the load carried by the asset leaving w is both less than and greater than—hence equal to—the amount loaded at w. If $X_{0w}(v) = 0$, the constraints can be seen to be nonbinding.

$$DX_{uw}(v) - Y_w + Y_u \leq D - d_w,$$

$$DX_{uw}(v) + Y_w - Y_u \leq D + d_w \text{ for } u \epsilon P, w \epsilon P_+, v = 1,2, \ldots, V;$$

if lift asset v travels from u to w (a POE), the load carried by the asset leaving w is both less than and greater than—hence equal to—the load

carried leaving u plus the amount loaded at w. If $X_{uw}(v) = 0$, the constraints can be seen to be nonbinding.

$$DX_{uw}(v) - Y_w + Y_u \leq D + d_{w-n},$$

$$DX_{uw}(v) + Y_w - Y_u \leq D - d_{w-n} \text{ for } u \epsilon P, w \epsilon P_-, v = 1,2, \ldots, V;$$

if lift asset v travels from u to w (a POD), the load carried by the asset leaving w is both less than and greater than—hence equal to—the load carried leaving u less the amount delivered to w. If $X_{uw}(v) = 0$, the constraints can be seen to be nonbinding.

The following three sets of constraints refer to "hard windows" that cannot be violated. With these hard windows, there may be no feasible solution to the problem. If the windows are soft, these last constraints are omitted and penalties for violating the windows are added to the objective function.

$$a_u \leq T_u \leq b_u \text{ for } u \epsilon P;$$

all nodes must be visited within their windows.

$$a_0 \leq T_0(v) \leq b_0 \text{ for } v = 1,2, \ldots, V;$$

all lift assets must leave the depot within the depot departure window.

$$a_{2n+1} \leq T_{2n+1}(v) \leq b_{2n+1} \text{ for } v = 1,2, \ldots, V;$$

all lift assets must arrive back at the depot within the depot arrival window.

The objective function to be minimized is

$$\sum_{v=1}^{V} \sum_{u=0}^{2n+1} \sum_{w=0}^{2n+1} c_{uw} X_{uw}(v) + \sum_{u=1}^{2n} f_u(T_u) +$$

$$\sum_{v=1}^{V} g_v[T_{2n+1}(v) - T_0(v)] + \sum_{v=1}^{V} \sum_{u=1}^{n} KX_{0u}(v)$$

where $f_u(T_u)$ is the penalty cost associated with beginning the service at node $u \epsilon P$ at time T_u and $g_v[\tau]$ is the penalty associated with lift asset v traversing a route of length τ. These penalties must be in the same units as c_{uw}. The choice $c_{uw} = f_u(T_u) = g_v[\tau] = 0$ will minimize the number of assets required to meet all of the requirements. In the situation with soft windows, choosing $K = g_v[\tau] = 0$ and

$$f_u(T_u) = d_{u-n}(T_u - b_u) \text{ for } u \epsilon P_-$$

$$= 0 \text{ otherwise}$$

minimizes "tons-late."

Other Considerations

One set of real-world constraints not accounted for in this model formulation has to do with finite capacities of POEs and PODs. To illustrate, suppose movements i and i + 1, of sizes d_i and d_{i+1} respectively, both emanate from the same POE and suppose that this POE has the capability to load one lift asset at a time at a rate of r tons per hour. In the problem formulation, the service times

$$s_i = d_i / r, \; s_{i+1} = d_{i+1} / r;$$

the time to load a movement at this POE is the size of the movement divided by the loading rate. If movement i was to be carried on one asset and i + 1 on a second asset then there is the constraint

$$T_i + s_i \leq T_{i+1} \text{ OR } T_{i+1} + s_{i+1} \leq T_i;$$

the start of the loading at "node" i or i + 1 cannot begin until the loading at the other is completed. In general, each POE and POD would generate its own set of such constraints, making the model even more complex than it already is.

A major departure from reality in this model is the assumption that all lift assets are identical and reside in a common depot at time a_0. First, this precludes using the model for both airlift and sealift. An additional preprocessing step must be taken to assign movements to sea or air and each would be treated seperately. Second, assuming that sealift is the major concern, the merchant fleets that would be used in the sealift do not consist of identical vessels—there are marked differences between ships. Third, at any instant of time, these ships are scattered over the world's oceans, some of them fully loaded with nonmilitary cargo. To take part in the sealift, they would have to put in at some nearby port, unload, and proceed to the "depot" where they could begin their operation, at some considerable delay.

Considering the number of ships that would be used in an operation, it can be questioned whether multiporting is a good idea. It might be desirable to route materiel that would be originally designated for geographically close POEs to be picked up by the same vessel making multiport calls to the same POE in order to eliminate the time "overhead" that multiporting generates at each port. With large numbers of ships available to assign to POE-POD channels, the SCOPE transportation models could be used. At the very least, SCOPE would provide an lower bound on what could be accomplished if multiporting was used.

SOLUTION ALGORITHMS

Computer algorithms to solve mathematical programming problems will require some number of calculations. Some algorithms are *polynomially bounded*; it is known that the number of calculations that would be required in the worst case that might arise is polynomial in the number of nodes, N. It is known that vehicle routing problems in general, even without time windows, are *NP hard.* This means that no polynomially bounded algorithm has yet been found, and worse, if a solution is suggested and claimed to be optimal, it would require as many calculations to verify optimality as it would to derive the optimal solution from scratch. It has also been shown that simply obtaining a *feasible* solution to the dial-a-ride problem with time windows is *NP complete*; no polynomially bounded algorithm has yet been found, but the feasibility of a proposed solution can be verified in polynomially bounded time.

NP hard algorithms tend to be exponential, requiring, in the worst case, a number of computations proportional to 2^N. Thus, every time a node is added, the problem size could double and this rapidly attenuates the advantages that even parallel processing might bring; the number of calculations for a 300 node problem (149 movement requirements) could be proportional to 2×10^{90}. The solution algorithms that exist for such problems tend to be heuristic.

Psaraftis et al., 1990, have investigated the shoreline problem for a *single* ship. The ship had a number (N) of ports to visit, each port had an earliest availability time for the cargo, loading was instantaneous, and there was no sequencing requirement (no requirement to pick up cargo at a POE before delivering it to a POD). The objective was to minimize the time to complete all visits. If the shoreline can be approximated by a convex hull (so that travel times $t_{ij} = t_{ik} + t_{kj}$ for all $1 \leq i \leq k \leq j \leq N$), then the solution time is linear in N. This remains true even if "deadlines" (e.g., latest delivery times) are imposed on some or all of the ports. If the ship need not return to its depot at the conclusion of its tour, a dynamic programming algorithm is presented whose solution time is proportional to N^2; this algorithm cannot be extended to include deadlines. In the more general case where the convex hull approximation cannot be made, the value of these algorithms as approximations depends on the ratio t_{1N} to the sum of the $t_{k,k+1}$, which measures the deviation from the assumed condition.

The airline industry has had extensive experience in the use of integer programming algorithms. Gershkoff, 1989, treated the crew scheduling problem as a set partitioning problem. Flight legs are assigned to crews in the same (mathematical) way that movements are

assigned to lift assets. Gershkoff cites Bornemann, 1982, for the observation that "Combinatorial problems begin to explode for problems larger than 100 [flight legs] and become unmanageable for 200 or more." He uses a combined analytical and heuristic approach with manual adjustments often needed to make the derived solution conform to all of the constraints. Abara, 1989, has described a fleet assignment algorithm similar in structure to the dial-a-ride problem. His computational experience has been: "Using the IBM MPSX/370 and MIP/370 on an IBM 3081 machine, run times have ranged from slightly under two minutes for a two-aircraft-type problem to over sixty minutes for a problem involving four aircraft types." He points out that a 400 flight leg schedule with 60 airports and three aircraft types would involve approximately 6300 columns (integer variables) and 1800 rows (constraints) in the linear programming formulation of the integer programming problem, and he has observed that run times tend to increase faster than linearly with increases in the number of rows plus columns.

Solomon, 1987, has examined several heuristics. He concluded, on the basis of some test cases that did not take vehicle capacity into account, that the most effective heuristic was an *insertion algorithm*. A modification of this algorithm taking the capacities into account was discussed by Solanki and Southworth, 1989, who presented it not as a method of creating the initial schedule, but as a method of updating the schedule when new, unplanned movement requirements arise. It also takes into account the possibility that certain of the POEs and PODs will have periods during which they cannot be used for pickup or delivery.

THE NEAR-TERM FUTURE

There have been some major advances in mathematical programming techniques recently, based on both hardware and software developments. The AT&T KORBX system combining parallel processing hardware with 256 MB of memory and software consisting of four algorithms based on Karmarkar's interior point method has solved a 700,000 variable, linear programming problem with 192,000 constraints in four hours; however, none of the variables was constrained to be integer. KORBX has been evaluated by the Military Airlift Command (see Carolan et al., 1990) on a set of pure network problems, multicommodity network flow problems, problems generated by the channel routing model for Europe (used to design a set of cargo routes to be used to service European bases), and operational support airlift

models. The longest solution time was required by a multicommodity network model with 33,874 rows (constraints) and 105,728 columns (variables) used to evaluate MAC's capability of moving patients from a European theater to U.S. hospitals over a 20-day time frame. One of the KORBX algorithms was able to obtain the optimum solution in 17.7 hours while the other three had not yet reached optimality in 24 hours.

KORBX is not designed to solve integer programming problems; it is expressly designed for linear programs. Network problems (for example, the transportation model described earlier) are generally linear programming models whose mathematical structure guarantees integer solutions. The only exception to this guarantee occurs when there are multiple solutions. For example, consider a transportation problem with one optimal solution involving a shipment of one unit from source 1 to destination 1 and no units to destination 2 while one unit is shipped from source 2 to destination 2 and no units are shipped to destination 1. If the unit shipping costs are the same for all four origin-destination pairs, then another optimal solution will reverse the shipments: from source 1 to destination 2, and source 2 to destination 1. In fact, any linear combination will be optimum; source 1 ships a fraction f units to destination 1 and 1-f units to destination 2 while source 2 does the opposite. The interior point method of Karmarkar will *always* find one of these fractional values as the solution and does not provide a mechanism for determining any of the basic solutions that would give the integer solutions.

Most integer programming problems without the mathematical structure that leads to basic (and hence optimal) solutions that are integer (and this includes the dial-a-ride) are solved by "LP-relaxation," finding the solution to the linear programming problem and applying some technique (such as branch-and-bound) to obtain integer solutions by solving new linear programs. While KORBX might prove faster in solving some of the large-scale linear programs, some or all of this advantage might be dissipated by the property of finding nonbasic solutions when there are multiple optimums. These solutions will contain more nonzero variables than basic variables, thereby increasing the number of branches that may have to be made.

There are alternatives to KORBX. Research is proceeding on combining the better aspects of KORBX with the simplex method to provide a mechanism to obtain basic (vertex) solutions from interior point (edge or face) solutions to expedite computation. Non-KORBX code has also demonstrated some impressive accomplishments. A 2400 node "traveling salesman" problem that generates 3,500,000 zero-one variables—an NP complete problem—has been solved using a computer

code developed under an ONR contract and, hence, available at no cost to the military. The first run of the problem took 22 hours of computer time; it has been estimated that this time would be substantially reduced if the program ran on a newer, faster machine. Other mathematical programming codes, some of which have also been developed with ONR and AFOSR backing, are being tested.

The developers of the computer code used on the traveling salesman problem believe that NP complete problems will be routinely solved within the next few years. Their experience has been that real-world situations (as opposed to artificially generated data sets) rarely approach worst-case status. The data tend to be better behaved, and the convergence to optimality is fairly quick. For problems of requirements planning, where data tend to be highly aggregated (which reduces the size of the problem) and a run time of several days can be tolerated, mathematical programming approaches—with all of its associated benefits—should be feasible. With the advent of parallel processing algorithms, it might even become feasible to extend mathematical programming techniques to the more disaggregated, shorter time-frame problems of deliberate planning as well.

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